DRAINAGE ENGINEERING

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PREFACE

The purpose of writing the following pages has been to present a general treatise on the drainage of agricultural lands. An attempt has been made to outline the various questions that should be considered in taking up a drainage problem, and to put into brief but comprehensive form the principles involved in the design and construction of drainage works.

The activities of the past few years intended to increase and improve agricultural areas through drainage, have greatly enlarged the application of engineering and scientific studies to this character of work. In addition to unwatering and reclaiming natural swamp and overflow lands, of which there are many millions of acres, principally in the humid sections of the United States, large drainage problems have developed and are still developing in the arid regions, as a result of irrigation. It has been estimated on irrigated lands generally that about one-fourth of the total area becomes unfit for profitable cultivation unless protected by drainage.

As a branch of Engineering, drainage presents many interesting and difficult problems. On account of the many varied and uncertain factors relating to soil and ground water conditions, it is difficult to formulate general laws governing many features of it. Each particular problem requires special study for economic and efficient results. The subject involves a study of the soil, hydrographic conditions, and also the location, design and construction of waterways for carrying away the excess supply. The effect of drainage upon the soil embraces questions of agriculture and soil physics. In every drainage enterprise economic questions are also involved.

The principles and methods I have endeavored to outline have been slowly developed through many years—even centuries. It is impossible, in most cases, to determine to whom the credit for them belongs. I have attempted, where possible, to give appropriate references throughout the text. Acknowledgment also is made to all whose writings I have read, to engineers whose coöperation I have had in working out drainage problems, and to many friends who have kindly assisted me in the work.

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CHAPTER I

SOILS

General Statement.—Drainage on cultivated lands is primarily to improve conditions by changing or regulating the water content in the soil. Its ultimate purpose is to bring about a condition of soil moisture best adapted to plant growth. To accomplish this result some of the fundamental facts concerning soils should be known and given consideration. Among the questions, relating to soils, that should be considered are those pertaining to soil formations, and the variations due to the physical and chemical action of the elements upon them.

By the term soil there is usually meant the more or less friable or top portion of the earth's crust. It is this that serves as a foothold for the growth of plants and also provides a source from which their food and moisture may be taken. The various properties of soils, especially their chemical compositions and the values of different constituents as plant foods, are subjects that can not be taken up in a treatise on drainage. Neither is it necessary that they be considered except in special cases where soils contain harmful alkali salts that must be removed. It is necessary, however, to consider the physical properties of soils, especially insofar as these properties affect the moisture content and the movement of water through them. In this connection the depth and structure of the soil and the materials of which it is composed are important factors.

The upper portion of the earth's crust may be divided into two classes commonly known as soil and subsoil. This classification is primarily for the purpose of drawing a line of demarcation between the different materials with which the engineer is required to deal. Under this classification, soil indicates the upper or top stratum of material and the subsoil the material or materials immediately below. A soil for example, may be designated as sandy loam and the subsoil as clay, sand or gravel.

Ordinarily there is a change in the character of material at depths ranging from one to eight feet below the surface. Cases are frequently found, however, where the material is uniform to depths of from ten to thirty feet, while in some instances these figures are greatly exceeded. It is thus seen that soil as here defined is subject to wide variations in thickness or depth.

Classification.—Soils may be classified in regard to their drainage properties as porous, or water-bearing, and non-porous. These terms are relative only, since there are no soils through which water will not pass, to a limited extent, under proper conditions. The rate at which water moves through some of the finely divided clays is, however, very small. These materials consequently must be considered as non-porous when viewed from a practical standpoint of drainage. Mixtures of these finely divided materials with those of coarser texture may be relatively water tight also. This is true when the finer and coarser materials are so graded that the interstices between larger particles are completely filled by the smaller ones. Examples of this kind are frequently found where clays and porous sands or gravels have been deposited together.

Of the materials that may be considered as porous, from a drainage viewpoint, are sands, gravels, fissured or broken clays, and not infrequently loose or broken rock. Sands and gravels, when not mixed with other finely divided substances, carry water freely, and may be regarded as the best examples, and probably the most reliable of the porous or water-bearing materials. Broken or joint clays are often sufficiently porous to permit the passage through them of large quantities of water; their structure, however, is generally irregular, the water travelling frequently in large veins or underground streams. These streams are often at considerable depths below the surface. In shale areas, or those having a shale subsoil the upper portion of the shale is usually fissured sufficiently to permit a slow flow or percolation of water through it. The same is true also of other soft rocks, such for example as gypsum.

The surface of contact between a tight or non-porous soil and a rock formation ordinarily permits the passage of water along it and is frequently the means of allowing subsurface waters to travel from one place to another. The soil above and the subsoil below may be each relatively water tight, yet the percolation between them may be large. Conditions of

this kind often lead to difficult drainage problems that require careful investigation and study for their solution.

Formation.—Soils are formed partly from natural rocks by the process of disintegration and partly from decayed organic matter. By far the greater part of the material composing the soil is of rock origin. The variations in the materials of the soil and the solid rocks from which they are derived are due to the long-continued action of the elements. This action is both physical and chemical in character. Through the agency of physical forces, such as the winds, flowing water, and temperature changes, the large rocks are gradually reduced to smaller sizes and eventually to fine particles. This action, no matter how slow and imperceptible it may be, is continually going on. In addition to the breaking up of the rocks, physical forces serve also to transport them from one place to another. Through the action of streams, rocks are constantly being worn away and the materials carried from the mountainous regions and deposited on the valleys or plains below. The finer rock and soil particles carried by the winds are continually being shifted from one place to another. This transporting action of the elements has a marked effect upon the character of the soil formation, and further reference will be made to it in a later paragraph.

The chemical action in rocks, more especially after they have been broken down by physical forces, still further separates them by disintegrating or breaking up the particles into their various elements. By this action the mineral constituents which serve as plant food in the soils are released and converted into such form that they may be assimilated. There are released also by these chemical changes soluble alkali salts which when present in any considerable quantities in the soil are detrimental to plant growth. In the arid sections, where alkali is more or less prevalent, its removal from the soils is one of the important functions of drainage.

Organic matter in the soil is the result principally of decayed vegetation. A small part of it, however, results from decayed flesh and bones of animals. The amount of organic matter in soils varies greatly due to different conditions under which they are formed, and also to the mode of formation. In the truly arid regions where, due to lack of rainfall, there is little or no vegetation, soils generally contain little or no vegetable matter. In the humid regions where vegetation is abundant, the content

of organic matter in the soil is frequently large. Cases are common on depressed or flat areas, that do not permit surface waters to drain freely from them, where the soil is composed entirely of organic matter to depths of many feet. The beds of former lakes and the valleys of sluggish streams that have been filled by vegetable growth are the best examples of soils formed wholly or nearly so from organic matter.

The character of a soil is dependent to a great extent upon the amount of vegetable or organic matter which it contains. Vegetation is consequently an important factor in the processes of soil formation. Vegetable matter undergoes marked changes in the soils before it reaches a form in which it can be assimilated as plant food. These changes are principally chemical in character They consist essentially of a breaking down of the highly developed organic forms into the simpler chemical compounds.

Variations In Soil Formation.—There are two fundamental factors upon which variations in soil formation principally depend, first—the materials from which the soil is formed, and second—the manner in which these materials are broken up and deposited. The different kinds of rock, when disintegrated by means of physical forces and chemical action, may result in widely different soils. These differences are both physical and chemical in character. The physical variations relate principally to size and shape of soil grains, or fineness of texture, and to the behavior of the soil when water is applied to it. In the latter may be included the absorbing capácity, and the power to resist the flow or percolation of water through them. Other differences, such for example as density, color, etc., are of lesser importance for the present subject.

Certain rocks, such for example as the shales, are reduced by disintegration to uniformly small particles and form soils of fine texture. Other rocks are less uniformly reduced by the process of disintegration and produce soils of coarse or varying textures. Sedimentary soils frequently vary greatly their character depending upon the materials from which they are originally formed and the selective action of water in transporting and depositing them. The presence of organic matter in a fine-grained soil has the effect of rendering it more open and pervious to water than it would be otherwise. This is due to the fact that the fine grains of which the soil is composed are further separated from each other. The clays, which in their

pure state are nearly impermeable to water, may be rendered pervious, to a certain degree, by adding organic matter to them. It is well known in irrigated sections, that soils, which, when first irrigated, are so tight that water can hardly be made to penetrate them, gradually become loose and friable by working vegetable matter into them. The addition of a small percentage of sand to fine-grained clays also tends to break them up and increase their porosity. The results, above described, which can be accomplished to a limited degree by artificial means have been, and are being accomplished on a gigantic scale by the slow action of natural forces.

Chemical variations in soils are due principally to the different constituents that are, or have been given up by various rocks during the process of disintegration. This difference in the chemical constituents furnishes an explanation why one soil contains a higher percentage of plant food than another. The adaptability of one soil to a particular plant is also due in large part to the presence of some chemical element specially favorable to the growth of that plant. As in the case of physical properties, the chemical properties are influenced and modified by the transporting, and resultant mixing of different materials in the process of soil formation.

Soils of the Humid and Arid Regions.—In the humid areas where soils are formed under conditions of copious rainfall, the action of water plays an important part, and in some respects changes the character of the soils from those of the arid regions. One of the principal effects of water on soil formation is to produce vegetable growth. This decays rapidly and becomes mixed with the rock elements during their disintegration. The result is the addition of organic vegetable matter to the rock particles of which the soil is composed. Another important action of water is the leaching out and carrying away of portions of the soluble mineral salts that are released during the process of rock disintegration. Still another which is closely related to the leaching action is the compacting and rendering the soils less porous than when formed without the action of water upon them.

In the arid regions where soils are formed largely without water action, the growth of vegetation is limited and in many cases practically absent. The soils as a result of this contain little or no vegetable matter. The soluble salts which have been

released from the mineral rocks are not so completely leached out of the soils and carried away as is the case in the humid regions. Neither are the soils in the arid sections so completely compacted and impervious to the motion of water through them. In the humid areas there is a greater likelihood of the more or less mellow top soils being eroded and carried away due to frequent washings of heavy rainfall. The top soils on this account are as a rule thinner and the subsoils less porous. The percentage of water which sinks into the earth is less and that of runoff consequently larger in the humid than in the arid regions. The significance of this upon the varicus problems of drainage is important.

Effect of Leaching on Soils.—The leaching of soils by the frequent or continued action of water upon them during their formation has the effect of removing the soluble mineral salts. The salts that are formed by the breaking up and chemical disintegration of rocks are largely of an alkaline nature such for example as the sodium and potassium compounds. In the arid sections where little or no leaching takes place, on account of the absence of rainfall, the salts remain in the soils. It thus results that in these regions the soils are generally alkaline in character. Where soils have been formed in place or where they have been transported by wind action, the alkali content is mixed more or less uniformly in them. Where the action of water has taken part in the transportation the salts are less uniformly distributed. Examples of this are alkali sinks in desert regions. Here the alkali in solution is carried by occasional floods into low depressions, the water later evaporates and leaves the residue of salt on the surface. This process continued at occasional intervals for a long period of time results in forming lands strongly impregnated with alkali to a depth of many feet. Other examples of alkali deposits concentrated on the surface are where the salt laden waters have been brought up from underground sources by capillary action. The evaporation of the water leaves the salt on the surface. The latter condition is common, in the arid and semi-arid regions, adjacent to natural streams, and at the foot of slopes which yield occasional runoff due to rains or melting snow. In many cases this condition is created by artificial application of water. It consequently has an important bearing on the drainage of irrigated lands.

Reference has already been made to the leaching effect upon

FIG. A.—The desert before irrigation showing extreme dryness and lack of vegetation to supply organic matter to the soil.

FIG. B.—A swamp of the humid area showing heavy growth of vegetation.

(*Facing Page* 6)

PLATE I

FIG. C.—Steep side hill along which water found its way to the surface over a shale substratum.

FIG. D.—Silt deposits due to overflow, Colorado River Valley.

soils in the humid areas. This together with the effect of decayed vegetable growth has resulted in rendering the soils on those areas neutral or acid in character. The leaching action by removing the soluble materials has also caused the soils and subsoils to become more tightly compacted. On account of fundamental soil differences, and also differences in water supply, drainage in the humid and arid regions are in many respects separate and distinct problems.

Stratification of Soils.—In the processes of forming transporting and depositing soils various agencies are constantly at work tending to modify their character. One of the results of these agencies is stratification. It is produced ordinarily by the action of wind or water in carrying a soil of one kind and depositing it over that of another type. The growth of vegetation and the subsequent covering of it by sediment frequently causes stratification.

The thickness of the various strata depend upon the character and duration of the particular agency causing them. They may vary from a small fraction of an inch to several feet in thickness. Some very interesting examples of stratification are to be found in valleys subject to overflow during the flood stages of torrential streams. In many cases these streams are supplied by several tributaries coming from areas of different geological formation. The sediment carried by one consequently differs from that carried by another. A flood coming from one section of the water shed will overflow the lands leaving a stratum of one kind of soil. This is followed by an overflow from another section and a different material is deposited. On account of the constant shifting of materials, and the different thicknesses deposited by different depths of silt laden waters any particular stratum may vary greatly in thickness, and in places, may disappear altogether.

The shifting of the course of streams over valley fills also produce stratification very irregular as to character. The bed of the stream usually consists of sand or coarse materials that are not readily carried in suspension. When a stream shifts to a new location the old bed is covered with a finer silt, thus there is formed a top layer of fine tight material underlaid by a porous stratum of sand or other material. The beds of most dry or ancient lakes are stratified due to materials having been brought into them from different sources.

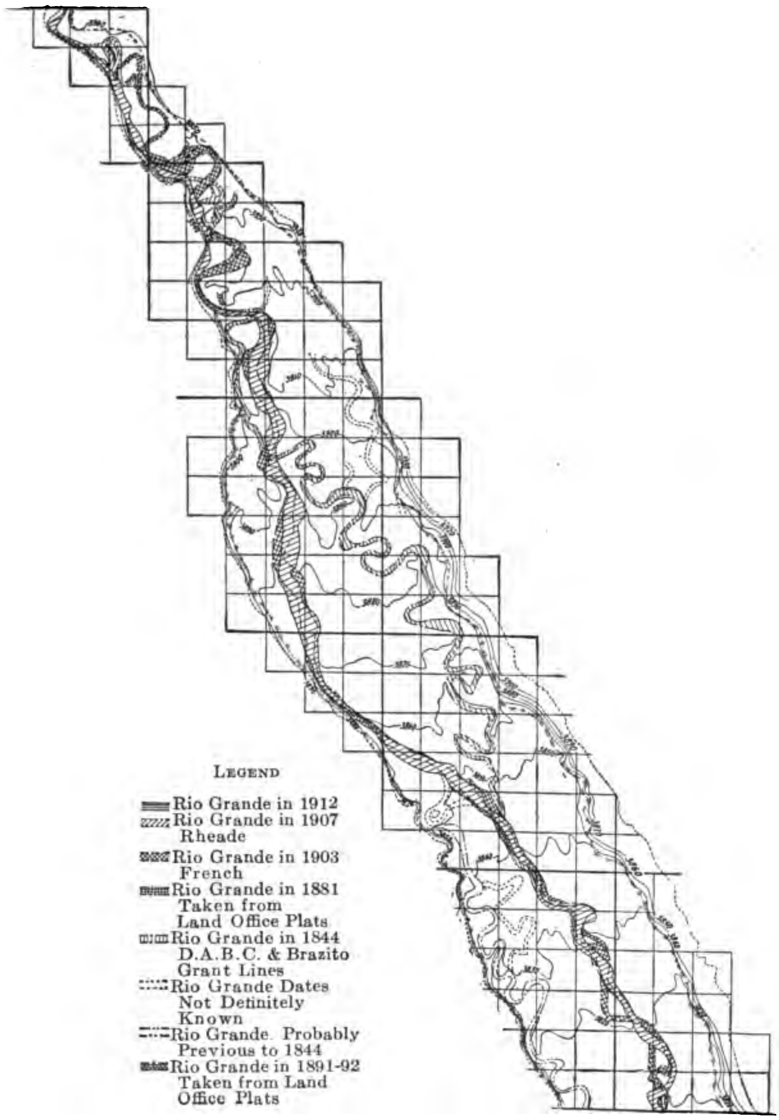

FIG. 1.—Map of a portion of Mesilla Valley, N. M. Showing old channels of the Rio Grande. From data compiled by U. S. Reclamation Service.

Soil Waters.—No soil, even in the extreme arid regions, is entirely free from moisture. The rock particles of which the soil is largely composed contain small amounts of water chemically combined with other constituents. This moisture, which is sometimes termed water of hydration, cannot be set free except by breaking up the structure of the rock particles. In all soils exposed to the atmosphere there is also a thin film of water surrounding and adhering to each of the individual soil particles. This film adheres so closely that it cannot be removed by any ordinary process of drying. It may be removed by artificial processes such, for example, as heating, but when so removed rapidly collects again when the soil is exposed to air at ordinary temperatures. Water which adheres to the soil grains and which cannot be removed by the ordinary processes of drying in air is known as hygroscopic water. Neither of the two forms of water above mentioned can be absorbed by plants, and consequently need not be considered in agricultural operations.

In addition to the above mentioned forms, water may exist in the soils in a partially or wholly free state. Water in a partially free state, sometimes known as capillary water, is held by capillary attraction in the minute spaces between the soil grains. It cannot be removed except by evaporation or by some force greater than that by which it is attracted to the walls of the capillary spaces or to the individual soil grains. It cannot be drained out of the soil by the action of gravity. It is, however, free to move over the surface of a soil particle or from one particle to an adjacent one.

Free water in a soil is that which entirely fills the spaces be tween particles not occupied by capillary water. It is free to move in any direction through the interstices of the soil, and may be drained out of the soil by the action of gravity. A soil of which the interstices are filled with free water is sometimes designated as saturated. One which contains capillary water only is designated as moist.

If an excavation such, for example, as an auger hole, or test pit, be made in a soil which is moist only, no water will collect in the excavation. If the excavation be made in a soil which is saturated, water will drain out of the adjacent soil and rise in the excavation to the upper limit of saturation. The upper limit of free water in a soil is usually designated as the water plane or water table. The depth of the water table below the surface

of the ground varies greatly, and depends upon the character of the soil and subsoil and also upon the amount of water which finds its way into them. Above the water table there exists

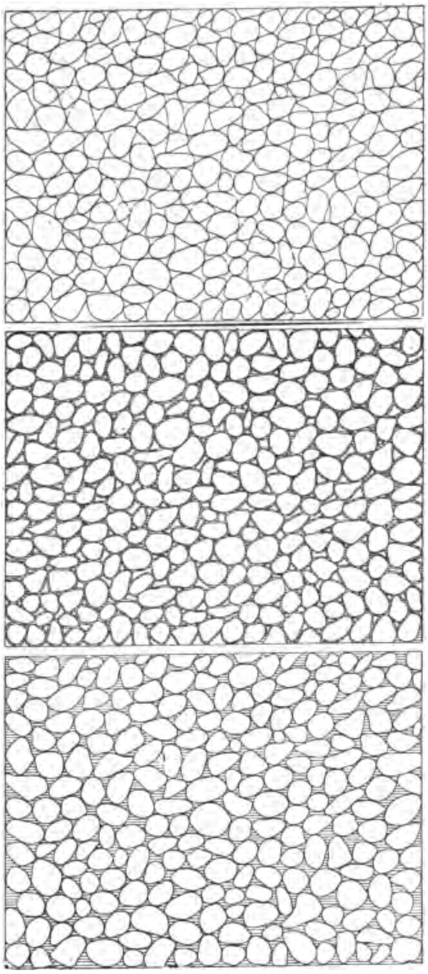

FIG. 2.—Ideal sections of dry, moist and saturated soils.

always a zone of moist soil the water content of which is brought up by capillary action from the free water below.

Capacity of Soil for Water.—The amount of water a soil can contain when fully saturated is the volume of the pores or spaces between the soil particles. It varies for different soils and depends,

first upon the relative sizes or grading of the soil particles and, second upon the amount of compacting to which the soil has been subjected. Ordinarily a soil composed of uniformly or nearly uniformly sized particles has a greater volume of pore spaces and a larger capacity for water than one composed of well graded materials. Also a soil when in a loose condition has its particles more widely separated and contains more pore space than when it is tightly compacted. The action of water upon a soil tends to bring its particles closer together. Water is one of the greatest soil compacting agents.

Fine grained clay soils, ordinarily, have greater capacity for water than the coarser grained sandy ones. Measurements that have been made on various types of soils under cultivation show that the pore space ranges from about 20 to 50 per cent. of the total volume.

The capacity of a soil for water, or its pore space, is not a measure of its absorbing power, that is the rate at which water will enter it under any given condition. Neither is it a measure of the rate at which water will percolate through it. These are dependent more upon the size than the total volume of the interstices. The total pore space in a soil may be relatively large and the size of the individual spaces so small, that water will move through it very slowly.

CHAPTER II

GROWTH OF PLANTS

Food and Moisture.—Plants, with a possible few exceptions, require for their existence and growth, first—a medium for the protection and expansion of their root system, second—food and moisture and, third—heat, light and air. The first requirement and, to a large extent, the second also is fufilled by the soil. It protects the delicate root branches from the direct rays of the sun and from sudden changes in temperature which they could not withstand. It equalizes the moisture and food supply furnished to the roots and prevents the latter being dried up and destroyed. It serves also as a medium to support the root system. The hair-like branches sent out from the main plant cling to the soil particles and are thus enabled to extend their growth through the minute spaces. It is by means of this intricate system of fine root branches that food and moisture are collected and brought to the plant stem.

Without the support and protection of the soil the roots would be less perfectly developed and the growth of the plant less rapid. This is well illustrated by the slow growth of plants and shrubs on rocky slopes where the soil covering is very limited. Examples of imperfect growth in plants are also found in shallow soils underlaid by subsoils of hard material, that the roots cannot penetrate. A soil through which the roots can extend their growth is one of the essentials to plant life and development. Holding and regulating the water supply is another important and necessary function of the soil. How this supply is taken up by the plant will be discussed later.

The food of plants is in general supplied by the soil. It comes principally from the mineral constituents that result from the breaking down of rocks in the process of soil formation. Prominent among these plant foods in the soil may be mentioned, potash, phosphoric acid, lime and magnesia.

The presence of organic matter in the soil is also necessary to the successful growth of plants since the supply of nitrogen comes largely from this source. Whether or not organic mat-

FIG. A.—Alfalfa roots growing in soil underlaid with hardpan at a depth of about three feet.

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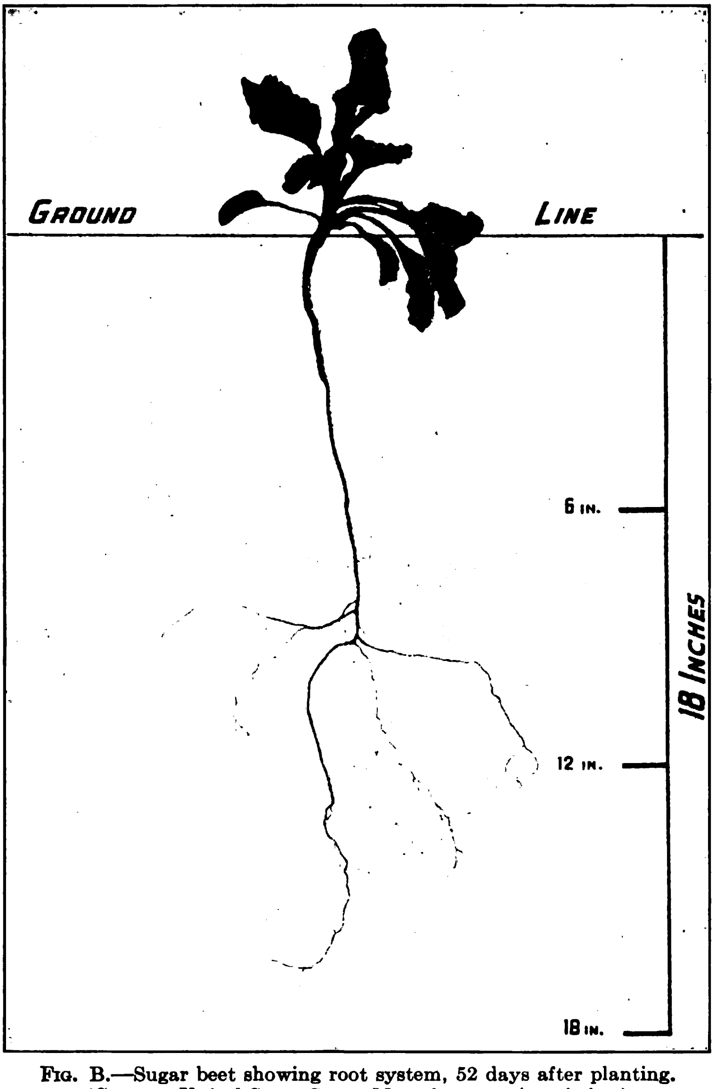

FIG. B.—Sugar beet showing root system, 52 days after planting. (*Courtesy United States Sugar Manufacturers Association.*)

ter is necessary in order to supply other than nitrogen, and to keep soils in proper tilth is a question upon which some differences of opinion exist. The fact that plants are supported and fed directly by the soil is one of the economies of nature.

It is possible and to a very limited extent practicable to supply food to plants by artificial means. This however must be done through the medium of the soil. Such operations, as, for example, the use of fertilizers, are generally limited to supplying certain elements only that are lacking in the soils. It is possible though to supply artificially to a soil all of the elements needed for the growth of a plant. In other words, a plant may be made to grow in a soil composed entirely of hard rock particles, or even glass balls, provided such soil is kept supplied with the proper amount of water holding the necessary plant food in solution. Such a soil would, of course, have but little capacity for holding moisture and plant food. These, on this account, would have to be added continually or at very frequent intervals. Such an experiment has no practical value other than it shows, first, that the food of plants is taken up in solution in water and, second, that food may be supplied to a plant from a source independent of the soil in which it is grown.

Absorption of Water by Plants.—From the foregoing paragraph it is seen that moisture in a soil is necessary in order that it may support plant growth. The water used by plants is all, or nearly all, taken from the soil, the exception being the small amount which under certain conditions is absorbed from the atmosphere. The food supply assimilated by plants is carried to them in solution. Water in soils is consequently essential to plant life. The quantity of water that a soil contains, the size and shape of the soil grains and the spaces between these grains are also factors affecting the absorption of moisture and food, and the consequent growth of the plant.

The water used by plants is taken from the minutely thin film which surrounds the individual soil particles. When this film is too thin or, in other words, when the soil reaches a certain degree of dryness the plant can no longer obtain the necessary supply from it. When the water film surrounding the particles is too thick, or when the interstices of the soil are wholly or in great part filled with water, absorption by the plant is retarded or suspended. Plants generally cannot absorb moisture from free water, nor from a soil the pores of which are entirely filled

with water. Since the food supply is carrried in solution any condition which prevents moisture reaching the plant interferes with its food supply also and prevents or retards growth. It is important in agricultural operations that the soil contain sufficient water for the needs of plants, also that the water content is not in excess of that which can be used by them.

Condition of Soil for Plant Growth.—The general requirements of a soil in order that plants may thrive in it may be stated as follows:

1. It must contain food and moisture for the plant's subsistence.
2. Its structure must be such that plant roots will penetrate it freely; it must also allow the free passage of water through it.
3. Its water content must be of the proper amount to allow free absorption by the plant roots.
4. It must be free from excess quantities of harmful salts or other elements that tend to destroy or prevent the development of plant tissue.

The character and amount of plant food available in a soil depends upon various factors, such, for example, as the kind of rocks from which it was formed, the vegetable matter that has been added to it and, what is of greatest importance in used soils, the care that has been practised in replenishing those elements taken away by growing crops. Plants absorb or take away from the soil some of its supply of food, and in order to maintain this supply it is necessary to return to the soil by means of fertilization and the addition of organic matter the elements that are being constantly exhausted. It is one of the inflexible laws of nature that the supply of any substance can be maintained only by the addition of an amount of the same substance equivalent to that taken away. This law must be recognized in order to insure continued success in agricultural operations.

Equally important to conserving the food supply is the question of maintaining the tilth and friability of the soil. It is necessary that plant roots be able to penetrate the entire volume of the soil bed in order to extract therefrom the moisture and food which they require. The fine root branches cannot easily force their way through hard strata, and where such exist in the soil the plant is limited in the amount of moisture and food it is able to obtain. It is essential also for plant growth that conditions be such that air can circulate through the soil.

Soils that are compact and non-friable may be improved by

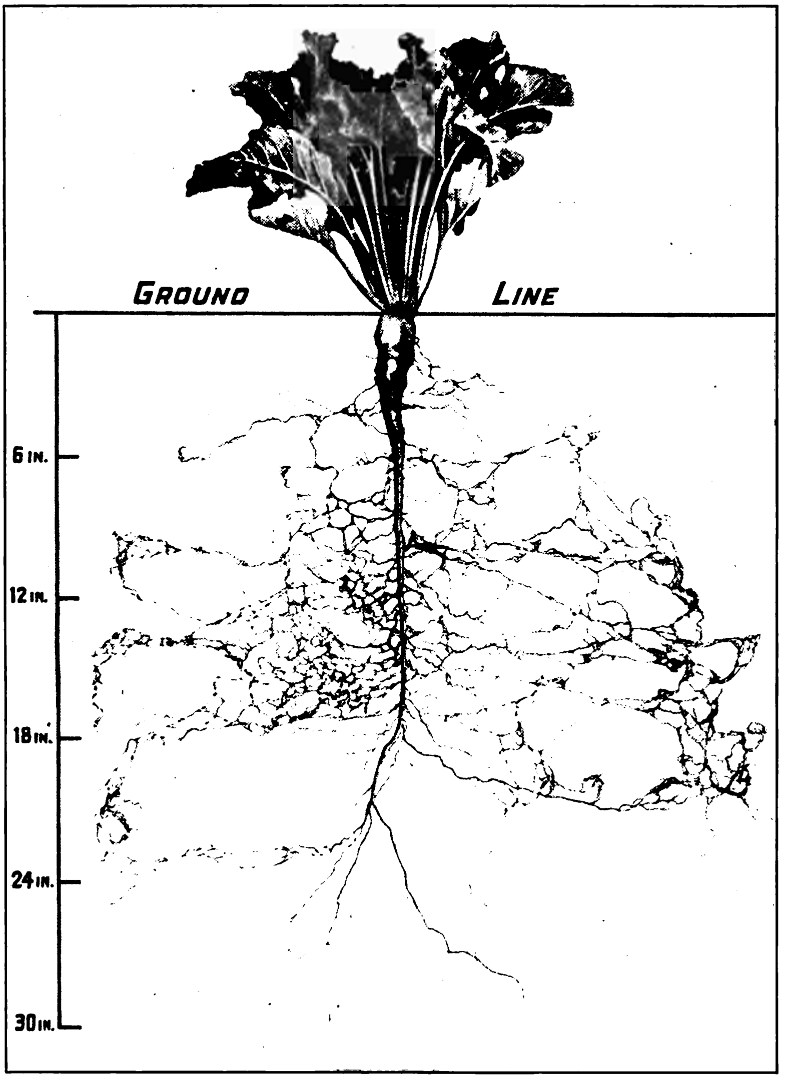

FIG. A.—Sugar beet showing root system, 84 days after planting.
(*Courtesy United States Sugar Manufacturers Association.*)

PLATE III

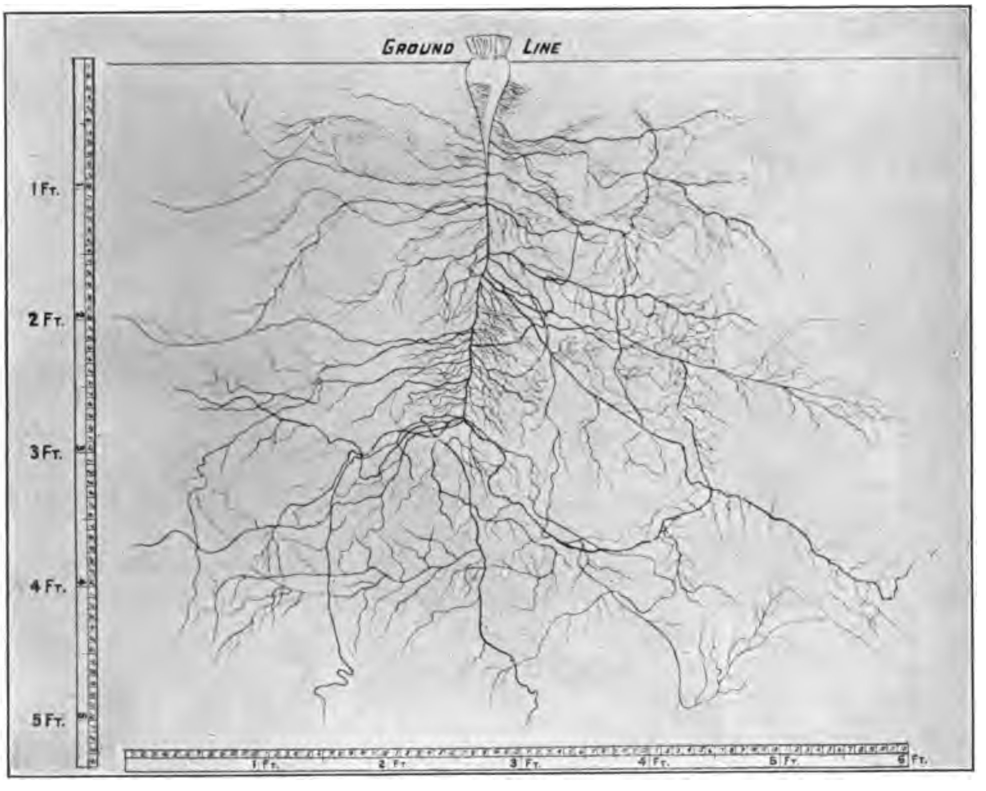

FIG. B.—Sugar beet showing root system, 132 days after planting.
(Courtesy United States Sugar Manufacturers Association.)

thorough cultivation, and the addition of vegetable matter. It must be recognized, however, that this process requires time and constant effort to produce results. A heavy clay soil can not be subdued and reduced to a readily workable one except by long cultivation and the turning back to the land of a portion of the vegetable matter that it produces. Attention must also be given to the kind of crops grown. Deep-rooted plants, such, for example, as alfalfa break up the soil and render it more porous; they also tend to the accumulation of vegetable matter in the soil by the expansion of the root system.

The amount of water required by a soil to be in the best condition for plant growth has been termed by some agriculturalists the optimum water content. It varies for soils of different texture and possibly, also, to a small degree, for different plants. It has been stated previously that the plant roots extract water from the thin film which surrounds the soil particles. It follows that the amount of water which will adhere to the particles in a fine-grained soil is greater than in a coarse-grained one, on account of the greater surface area of the finer particles. The results of investigations by soil experts indicate that the optimum water content varies roughly from about 20 per cent. by weight of dry soil, for clays, to about 5 per cent. for coarse sands. The optimum water content corresponds closely to the amount which renders the soil most friable and in best condition for cultivation. Above this amount the pores are partly filled and conditions are less favorable for cultivation, and plant growth. When this condition continues for some time the soil becomes compacted and the volume of pore space decreased. The air is also driven out of the pores and there results a condition commonly known as water-logging. Plants cannot thrive in a water-logged soil.

When the water content in a soil is reduced below the optimum amount the lower limit from which plants can absorb their full supply of moisture is approached. If the water content falls below this limit the growth is retarded and wilting finally takes place. The range between too wet and too dry for the best condition of soil for plant growth, is a relatively narrow one and varies greatly for soils of different textures. It is given by some investigators at from 1 to 5 per cent. of the weight of dry soil. This is equivalent to saying that for the best growing conditions the water content should not vary more than from about 1 to 5 per cent. of the weight of the soil.

On account of their larger capacity for holding water the finely divided or, as they are generally termed, heavy soils will support plant growth for a longer period without water being applied to them than is the case with coarse sandy ones. The total amount of water required to moisten a fine-grained soil sufficiently for plants to grow in it is also greater than for a coarse-grained one. In order to wet them to similar depths more water must be applied to fine-grained clay soils than to sandy ones. More frequent applications, however, are required on sandy soils. It is to be understood that the above statements regarding fine-grained soils refer to those that are broken up and in a friable condition and not necessarily to those that are tightly compacted.

The amount of water actually required by sandy soils must not be confused with the amount that may be applied to them in particular cases without increasing the water content above the optimum amount. On sandy soils, especially those provided with adequate under drainage, any excess of water applied quickly passes downward and leaves the top soil with only a limited amount of moisture. Generally this amount is that necessary to support plant growth. The same holds also, to a certain extent, for the less porous soils. A lack of understanding of these conditions has led to the oft repeated error that sandy soils require more water than the heavier clays in order to support plant growth upon them.

Certain soluble mineral alkali salts commonly found in the soils of the arid regions are detrimental to most forms of vegetation, and in sufficient quantities will prevent the growth of useful plants. The principal alkali salts of this nature are Sodium Carbonate (Na_2CO_3); Sodium Chloride ($NaCl$) and Sodium Sulphate (Na_2SO_4); there are others, however, the effects of which are less apparent. Of the alkali salts Sodium Carbonate (black alkali) is the most dangerous and also the most difficult to remove from the soils. One of the effects of this salt is to decrease the porosity of the soil and thus prevent free movement of water through it. The washing out of alkali from a soil which contains any considerable quantity of Sodium Carbonate is, on this account, a slow and difficult process. The limit of tolerance of plants for different alkali salts in the soil as given by some investigators is as follows:

Sodium Sulphate	1.00 per cent.
Sodium Chloride	0.50 per cent.
Sodium Carbonate	0.05 per cent.

The amount of alkali that a soil may contain without seriously impairing it for the growth of plants depends upon the kind of alkali, the character of the soil and also that of the plant—whether alkali resisting or not. The manner in which a soil is handled is also important in resisting the effects of alkali. On account of these various factors it is difficult to fix a minimum alkali content below which a soil may be considered safe. Chemical determinations of the quantity and character of alkali in a soil serve as an indication of its possibility to produce crops, and, within certain limits, reliable deductions may be made from such data. It cannot be said, however, that the amount of alkali sufficient to prevent plant growth under one set of conditions as regards soil, water, etc., will have the same effect under different conditions. Much also depends upon the distribution of the alkali, that is, whether concentrated, either near the surface or at some depth below it, or whether mixed uniformly through the soil.

It is generally held by agriculturists that the action of alkali in destroying a plant takes place at or near the surface of the soil. Some alkalis, if sufficiently concentrated, will, however, destroy plant tissue wherever it is brought into contact with them. The action which ordinarily takes place is believed to be that of extracting moisture from the plant. At the surface the soil and the salts which it contains lose water rapidly, due to evaporation. The attraction of the salts for water when in a dry state is so great that moisture is taken from the plant by them. It thus results that a portion of the water that has been absorbed and brought up by the plant roots is taken away before it reaches the stem and the plant is left to die for lack of food and moisture. If the top portion of the soil can be kept free from alkali this surface action will be avoided; also, if the surface of the soil is kept constantly moist the action of the alkali upon the plant is reduced.

The distribution of alkali in a soil may be changed by the movement of water through it. If this movement is upward the dissolved salts will be carried from the lower soil strata to the surface and there deposited when the water is removed by evaporation. If the water movement is downward the salts will move downward and away from the surface. On account of the movement of alkali in solution it is possible to reduce the quantity of harmful salts by washing them out of the soil.

Zone of Plant Growth.—That portion of the soil in which plants find support for their root system and from which they take their food and moisture is commonly termed the zone of plant growth. It is in this zone that proper soil conditions must be maintained in order that plants may grow successfully. The depth of the zone of plant growth varies greatly with soil and moisture conditions and character of plants. Some plants extend their roots but a few inches into the soil while others penetrate it to a depth of several feet. Annual plants such as the cereals, and many of the grasses are shallow rooted. Trees, shrubs and some of the leguminous plants, of which alfalfa is a notable example, are generally deep rooted. Where the supply of moisture is limited plant roots will force themselves deeper into the soil in order to reach a sufficient supply for their existence. When there is an excess of moisture, or if free water exists in the soil at a short distance below the surface, the growth of plant roots will be confined to shallow depths. The depth of the zone of plant growth consequently may vary greatly for the same plant under different conditions.

The roots of many trees and shrubs and also those of alfalfa have been known under certain conditions to extend to depths of from ten to twenty feet and even more in extreme cases. The conditions which promote root growth of this kind are open subsoil, a low water table and a small moisture content in the top soil. A hard compact subsoil or a high water table will prevent deep root growth and the same plants, that under the conditions first given, would have root systems from 10 to 20 feet deep, might under the second condition extend their roots to depths of only 2 or 3 feet. The deeper the roots penetrate the soil, or in other words, the deeper the zone of plant growth, the greater the food supply made available for the plant. It is consequently important that the soil be friable and porous and that it contain the proper amount of moisture to the depths that plant roots will normally penetrate.

The lower limit of the zone of plant growth, as may have been inferred from the preceding statements, is fixed by various conditions. It may be the limiting depth to which the particular plant will extend its root system, or it may be a hard impervious stratum which the roots cannot penetrate, or it may be soil from which the plant roots can absorb no moisture on account of the absence or excess of water in it. The latter condition prevails

when the water table rises too near to the surface of the ground. It consequently has a direct and important bearing on the question of drainage.

Excess Water in Soils.—By this is meant any water above the quantity necessary to maintain soils in the best condition for cultivation and growing of crops. It has been stated that the effects of excess water in soils are to prevent the growth of ordinary plant roots, to produce a water-logged condition, and in the arid areas to bring harmful alkali salts to the surface. Another important effect which may be found in the humid regions is to produce an acid condition, or what may be designated as sour lands.

The capacity of a soil for holding water, as stated in Chapter I, depends upon its character, that is upon the relative size and grading of the particles which compose it, and the degree to which these particles are compacted or brought into contact. It follows that the capacity of a soil may vary depending upon its condition. The quantity of excess water which it may contain is also a variable one.

It may be stated that all water which will drain out of a soil, if given a free outlet, is excess water and cannot be used by ordinary plants. It is true also that very fine textured closely compacted soils may contain capillary water in excess of the amount that plants can use.

Where the interstices are so small that the attraction of the soil particles on the water between them, or capillary attraction as it is called, is equal to or greater than the attraction of gravity for this quantity of water the pores will remain filled. Such a soil will not drain until its physical condition has been changed. A soil may also contain excess water with its pores but partly filled. In this case also it is necessary that it be broken up and the capillary action reduced before it can be drained and brought to a condition best suited for plant growth.

Soils of the character mentioned above will become dry if their supply of water is taken away and they are exposed for a sufficient time to the drying action of the atmosphere. This drying process may take place very slowly in finely graded and closely compacted soils.

CHAPTER III

WATER SUPPLY

Sources of Soil Water.—Water in the soil is the result either of rainfall directly on the surface, or its artificial application through irrigation. From the latter there result also some indirect sources of soil waters such, for example, as leakage from natural or artificial channels or reservoirs. Were the water which falls on the surface, in the form of rain, or that which is applied to it artificially, exactly equal in amount to that required for plant growth no excess would result and drainage generally would be unnecessary. This condition, however, is seldom found under natural rainfall conditions and seldom also is it accomplished under artificial applications of water. The rainfall, as

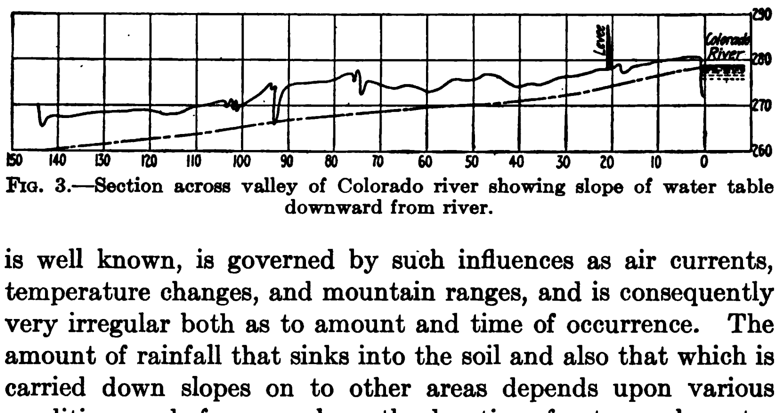

FIG. 3.—Section across valley of Colorado river showing slope of water table downward from river.

is well known, is governed by such influences as air currents, temperature changes, and mountain ranges, and is consequently very irregular both as to amount and time of occurrence. The amount of rainfall that sinks into the soil and also that which is carried down slopes on to other areas depends upon various conditions such, for example, as the duration of a storm, character of soil and steepness of slopes. On account of this irregular distribution portions of the soil receive more than it can absorb and use for plant growth. In order to keep the soils in fertile and productive condition the excess, above what can be beneficially used, must be removed.

Rainfall.—The supply of water which reaches the soil in the form of rain or snow differs in some respects very widely from that applied artificially in irrigation. These differences generally relate to the manner of distribution and the time or rate at which

water reaches the soil. Under conditions of natural rainfall the water is distributed over the entire area regardless of whether cultivated or unfit for the growing of crops. The amount of rainfall may and does vary greatly for different years, and for different seasons of the year. It also varies for different localities when areas of any considerable size are concerned. When an area of limited extent is considered, say one that would be included within an artificial drainage system, the rainfall generally may be regarded as fairly constant over it. This fact is important in determining the amount of runoff or excess water which an area will supply.

Generally it may be said that the amounts of water that must be removed from two adjacent small areas will be, roughly, proportional to the size of the areas. This, however, may be materially modified by topographic and soil conditions. Flat slopes and deep porous soils will absorb and retain more water than steep slopes and shallow soils.

One of the serious effects of rainfall, especially on moderate and steep slopes, is the erosion and carrying away of the loose top soils. The soil thus carried away goes in part to the building up and enriching of the flatter valleys below. A large part, however, especially during periods of heavy rainfall, is carried to natural waterways and eventually to rivers which discharge it into the ocean. It is this sort of action that supplies the thousands of tons of silt discharged by the Mississippi River, each year, into the Gulf of Mexico. It is possible, in many instances, by means of carefully laid out and properly constructed drainage systems to prevent, or reduce erosion on cultivated lands. The necessity for such action, in order to maintain the fertility of the soil, is apparent in many sections of the United States. Up to the present time, however, but little systematic work of this kind has been undertaken.

The character of rainfall, whether regular or intermittent, is an important factor in drainage requirements. The water which ordinarily must be removed by drainage is the excess above what soils can retain without becoming too wet for plant growth upon them. If the amount of rain that falls during a single storm period is not greater than the soil can absorb without becoming over saturated, no drainage is required. When the rainfall during a single period is large and greatly in excess of the soil's capacity there results an excess of water which should be removed.

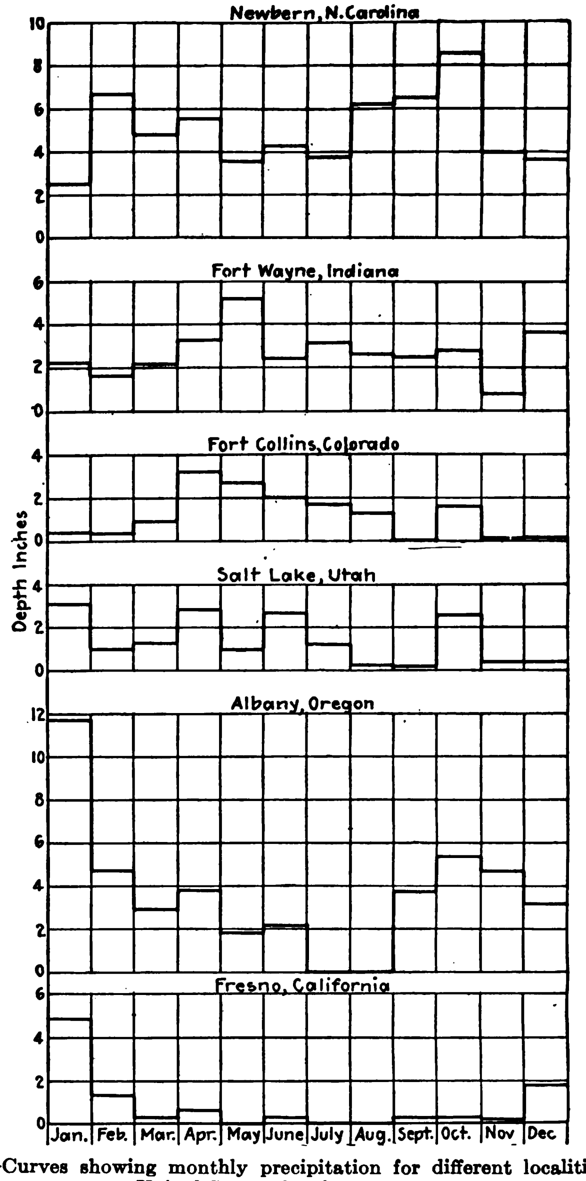

FIG. 4.—Curves showing monthly precipitation for different localities in the United States, for the year, 1914.

A heavy rainfall lasting but a short time, say for one hour or less, may result in large quantities of excess water reaching the lower areas and the greater portion of the soil over which the rain fell may remain in a comparatively dry state. The same amount of rainfall if distributed over a sufficient period of time to allow it to penetrate the soil would all have been absorbed.

The extreme cases given above relative to character of rainfall represent what may happen. It is seldom ever the case that rainfall occurs at such times and in such amounts as to exactly meet soil and crop requirements. There are, however, large variations in the character of rainfall in different sections of the country which must be studied in connection with the planning of drainage works.

Irrigation.—The artificial application of water to soils, in many ways, may be regarded as ideal. It is possible, theoretically at least, to control the supply both as to amount and time of application to suit exactly the needs of growing plants. The amount of water applied at one time may be varied for different crops and soil conditions. Similarly the period of application may be made long or short and the moisture content in the soil kept at the proper amount for plant growth. Irrigation also permits water being applied to such areas only as are used for growing crops and, to a large extent, eliminates the waste of water into soils on non-used lands.

While it is theoretically possible to produce perfect conditions under irrigation, the artificial application of water presents many practical difficulties that require long practice and a high degree of skill to master. In order that irrigation may be carried on in a perfect manner it is necessary to know first the amount of water required by a particular soil or crop and, second, to have processes so perfected that exactly this amount may be applied.

Concerning the amount of water that should be used there is a wide difference of opinion among irrigators, and exact knowledge on the subject is difficult to obtain. It is well known that it differs for different crops and climatic conditions. Soil conditions, while they probably affect but slightly the total quantity of water required for a particular crop, are important factors in determining how water should be applied.

The distribution of water to soils uniformly, and in the quantity desired presents one of the most difficult problems in irrigation operations. The methods of applying water vary greatly in

detail. They consist essentially of flooding the surface to the depth required or of running water over it or through furroughs a short distance apart until the required amount has been absorbed. The first method is applicable to relatively flat areas

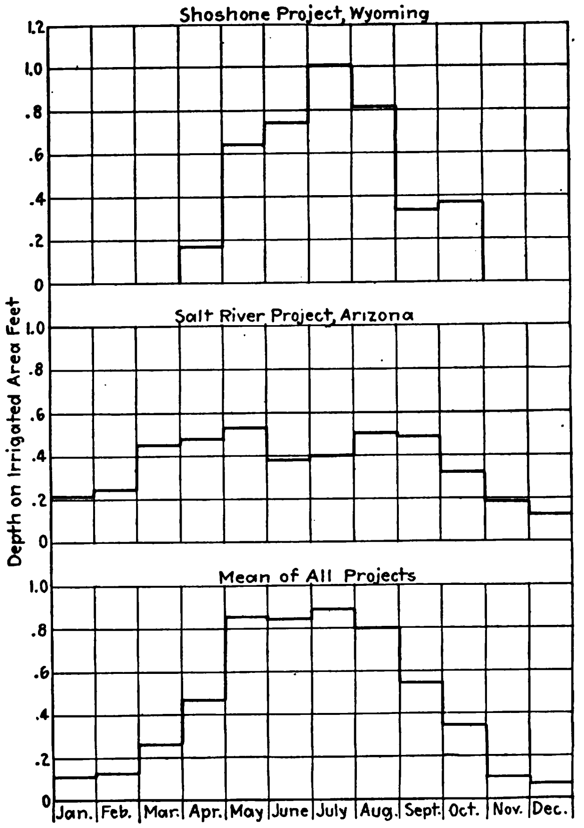

FIG. 5.—Curves showing by months quantities of water diverted for irrigation, in terms of depth on irrigated areas, on U. S. Reclamation Service projects, compiled from Annual Report for 1914.

where water can be held in place by low borders. The second method is more applicable to lands having sufficient slope to allow water to flow freely over them.

Whatever method of irrigation is employed a portion of the water applied to the soil is likely to be wasted. The wastes resulting from irrigation are of two kinds, surface and underground.

Surface waste results generally from water being applied to an area at a greater rate than that at which the soil can absorb it. It may be due also to an unequal distribution over the surface, thus allowing the water to collect in small streams or rivulets. Surface waste is most common on steep or moderate slopes, where the soils do not absorb water freely.

Underground waste may be defined as water which has passed below the zone of plant growth. It is common on soils underlaid by porous materials, such as sand and gravel, and results from applying to the surface at one time more water than the soil can retain.

Application of Water to Soils.—In order to avoid waste in irrigation it is of the utmost importance to regulate the amount of water to suit crop and soil conditions. It is necessary also to distribute the water evenly over the surface in order that it may be absorbed by the soil and none of it contributed to surface or underground waste.

The total amount of water required for the growth of plants is the amount that they will transpire plus the additional amount evaporated from the surface of the soil. To enable the process of transpiration to continue the soil must be kept, at all times, in a moist condition. Any excess or deficiency in the moisture content from the required amount retards growth. In order to keep the proper quantity of moisture, at all times, in the soil, it is necessary that water be applied at proper times and in definite amounts.

The frequency of application of water to soils and the amount that should be applied at one time, depends upon the quantity the soil can absorb and hold for plant use. In this the character of soil and the depth to which the roots penetrate are both important factors. Coarse soils, such as sand and gravel, will hold less water than those of finer texture. Water, on this account, should be applied to the former in smaller amounts and at more frequent intervals than to the latter.

Shallow-rooted crops absorb water from but a limited portion of the top soils, the amount that can be held in the soil available for their use is, consequently, less than for deep-rooted ones. Here also small, but frequent, applications of water are necessary.

The proper application of water requires a knowledge of the properties of the soil for absorbing and retaining moisture, and also a knowledge of plant requirements. One of the principal

causes of excess water in irrigated lands is the application, at a single irrigation, of more water than the soil can absorb and retain.

Excess Application of Water.—When the quantity of water applied is more than soils can absorb and retain waste is the result. This waste, as above stated, may be either surface or underground or both. In some special cases the net results of excess application may be simply a loss of water; generally, however, waste in irrigation results in damage to soils which is of far greater importance than the value of the water lost.

Surface waste is ordinarily carried in part at least to natural water-ways or drainage channels. There is, on this account, less danger of subsoils becoming saturated from it than from underground waste. Surface waste does, however, cause damage through the flooding of low areas over which it flows, and also through a part of it being absorbed by soils where not needed. In the latter case it contributes to filling up the subsoils. Its detrimental effect may be and frequently is felt at long distances from where the water was applied.

Underground waste passes through the soils until its downward motion is checked by some impermeable or semi-impermeable stratum. It contributes directly to filling the subsoils and to raising the water table. The water applied to soils in excess of what they can absorb and retain is lost so far as beneficial use to plants is concerned. It also becomes a source of danger and must be removed by means of natural or artificial drainage in order to insure protection to the lands.

The amount of water wasted into subsoils through the ordinary processes of irrigation is difficult to determine. Complete data on the subject involves a knowledge of the amount applied, the capacity of the soil for holding water, its condition as to moisture content before water is applied and also the maximum depth from which the particular plant can take up moisture. These, as heretofore stated, are variable factors. The capacity of a soil for water insofar as it relates to irrigation is not the total amount it is capable of holding, but the amount it will retain without becoming too wet for plants to grow in it. Soils, when properly irrigated, are not allowed to become dry; water is applied to them at sufficiently frequent intervals to prevent their moisture content falling below the minimum required for plant growth. The quantity necessary to be applied at one time is

that required to bring the moisture content up to the maximum required by plants. The difference between the moisture content that will allow plants to wilt and the optimum as has been stated already, varies from about 1 to 5 per cent. of the weight of the soil. If the maximum figure be taken the amount of water required to increase the moisture content in four feet depth of soil from the wilting stage to that best adapted to plant growth is slightly less than three inches over the surface. This assumes that water is applied to the soil as soon as needed and before the moisture content is reduced below that required by plants for their sustenance. Experience seems to indicate that the maximum amount of water that should be applied at a single irrigation is less than three inches in depth. Observations on drained soils show that the application of more than this amount, at one time, increases the discharge of the drains. For shallow rooted plants, which can take water from but a few inches below the surface, the amount of water given above is in excess of actual requirements. The same is true also for soils of low water holding capacities, such as coarse sands and gravels.

In irrigation practice surface waste is frequently regarded as the chief source of loss and little attention is given to waters that sink below the zone of plant growth. This is due partly to lack of definite knowledge regarding the amount of water that should be applied at one irrigation and partly to difficulties experienced in distributing a small depth of water evenly over the surface. The amount of water required for irrigation is usually stated as the depth needed to supply the land for a year or for an irrigation season. This does not give the number nor frequency of the irrigations required, nor the quantity that should be applied at each.

Losses from Canals.—Canals constructed in earth or other porous or semi-porous materials, lose a portion of the water which they carry through percolation into the soil. The amounts so lost depend upon the character of the material of which the waterway is composed, and also the degree of care used in compacting the material in place. It is sometimes impracticable in very porous soils to construct canals without providing some form of water-tight lining to prevent seepage. In finely divided silts and clays, or with clays and gravels mixed, it is possible to construct water-ways the seepage from which will be very small. When the canal is excavated in porous earth, the interior of the

section may be lined with more impervious materials. Where earth is used for this purpose it should be carefully selected, and also should be thoroughly compacted over the bottom and side slopes either by tamping and rolling or by being deposited in water. In the maintenance of earth lined canals care is necessary to prevent the water-tight lining being removed in cleaning the channels, or through excessive velocities of the water which they carry.

Canals which carry water heavily charged with fine sediment generally become silted so that leakage from them is of small importance. In rare instances the materials through which the channels are excavated are of such nature that but little leakage will take place through them. Such cases, however, are exceptional and ordinarily the losses from earthen canals represent a considerable portion of the total supply of water carried by them. The making of canals water tight by means of earthen linings is frequently impracticable on account of the lack of suitable material in the vicinity. To make earthen canals completely water tight it is necessary that they be lined with masonry or other form of impermeable material. This, on account of the high initial cost, is frequently prohibitive under the present state of development of irrigation farming.

The following table compiled from the records of the United States Reclamation Service gives the losses, for a series of years, from canal systems on various irrigation projects throughout the arid section of the United States.

No great accuracy can be claimed for the results given in the table due to lack of adequate means for making measurements in many cases. Their chief value lies in the lesson, which they teach, that earthen canals may be expected to lose a large part of the water which they carry. It is not possible from results of this kind to make accurate comparisons of losses in different soils or to determine the rate of loss for a unit area of canal section.

Earthen canals generally become more nearly water tight with use. This is due in part to the gradual disintegration of the materials forming the waterway and in part to the carrying of fine silty materials into the canals. The latter effect is particularly noticeable when the water supply is taken from a silt laden stream. An exception to the above is where canals are built on slopes so steep that the action of the water causes erosion on the bottom and slopes and also prevents the deposit of any silt that may be carried into the canal.

FIG. A.—Distributing irrigation water through furroughs.

FIG. B.—Distributing irrigation water by flooding.

(Facing Page 28)

PLATE IV

FIG. C.—Ground water standing on surface, the result of canal and irrigation losses.

FIG. D.—Leakage from canal.

TABLE 1.—SHOWING ESTIMATED LOSSES FROM U. S. RECLAMATION SERVICE CANALS

	1912			1913			1914			1915		
	Delivered to canal system, acre feet	Lost in canal system, acre feet	Per cent. of loss	Delivered to canal system, acre feet	Lost in canal system, acre feet	Per cent. of loss	Delivered to canal system, acre feet	Lost in canal system, acre feet	Per cent. of loss	Delivered to canal system, acre feet	Lost in canal system, acre feet	Per cent. of loss
Salt River	......	......	....	823,812	323,236	39.2	806,908	355,122	44.1	934,727	373,370	40.0
Yuma	96,409	33,136	31.3	127,307	40,731	32.0	205,207	56,952	28.1	246,786	49,311	20.0
Orland	34,048	6,816	20.0	40,489	10,769	26.6	50,146	13,066	26.0	52,347	14,323	27.3
Uncompahgre Valley	140,600	(a)6,689	4.8	168,573	8,517	5.0	185,227	13,959	7.5	264,060	32,789	12.4
Boise	474,640	132,276	27.8	328,174	111,027	33.8	406,986	139,028	34.2	183,811	56,035	30.4
Minidoka	508,994	136,070	26.7	618,186	132,160	21.4	549,582	236,886	43.1	609,434	241,468	39.6
Huntley	46,994	7,953	16.2	34,696	7,509	21.6	55,543	10,475	18.9	33,487	13,820	41.3
Milk River	1,256	538	42.8	4,267	1,394	32.6	3,276	1,335	40.7			
Sun River	20,392	4,078	20.0	24,628	9,379	38.0	24,762	9,828	39.7	15,538	6,475	41.7
Lower Yellowstone	15,404	6,625	43.0	30,088	15,631	51.9	25,769	13,488	52.3	40,141	17,320	43.1
North Platte	239,588	92,657	38.2	297,045	113,997	38.4	415,980	152,899	36.7	294,188	140,614	47.8
Truckee-Carson	134,059	54,260	40.5	169,243	64,791	38.3	225,564	62,467	27.7			
Carlsbad	85,086	40,778	47.9	86,560	47,198	54.5	87,900	48,756	55.4	79,530	38,677	48.6
Umatilla	54,256	15,064	27.8	59,552	16,322	27.4	62,728	25,147	40.1	55,331	24,236	44.0
Klamath	42,097	15,168	36.0	38,005	15,098	39.7	55,428	21,401	40.0	69,970	35,243	50.4
Belle Fourche	57,720	18,325	31.8	95,879	48,530	50.6	110,461	48,211	43.6	47,968	14,900	31.1
Okanogan	17,319	8,168	47.2	19,497	7,488	38.4	32,234	6,810	21.1	24,640	6,060	24.6
Yakima Sunnyside Unit	307,585	81,889	26.6	320,512	82,807	25.8	309,903	88,000	28.4	272,401	85,130	31.2
Yakima Tieton Unit	47,675	7,910	16.6	59,505	12,739	21.4	67,788	18,452	27.2	62,000	16,964	27.3
Shoshone	50,100	17,924	35.8	64,732	24,296	37.5	92,340	34,061	36.9	95,957	33,676	35.1

(a) Low losses on this project, attributed to return flow into canals.

It is evident from the preceding table that canal losses are, in a measure, responsible for excess waters in soils. These losses, it must be recognized will continue, probably somewhat diminished in amount, until it is feasible and financially possible to build canals of water-tight materials.

Surface Waters.—In planning and constructing drainage works a distinction is usually made between surface and ground waters. This distinction, which is largely one of convenience, is based primarily upon the location of the drainage supply and, with certain exceptions, has little or nothing to do with the character or quality of the supply. The disposal of excess surface waters is in many ways much simpler than that of excess ground waters. Each, however, present special problems that must be considered. Works which are sufficient for the one may be entirely inadequate for the other.

Surface waters, as the name implies, are those which are found upon the surface of the earth. They include waters which travel over or along the surface and also those which are deposited upon lands as the result of surface flow. The principal source of surface waters is direct precipitation in the form of rain or snow.

The removal of excess surface waters constitutes the principal drainage problem to be dealt with in the humid regions. As has been stated, heretofore soil conditions in those regions are such that the precipitation is to a large extent retained upon the surface. Saturation of soils by surface waters takes place through the downward percolation from the surface.

Ground Waters.—By the term ground waters is meant those which are found below the surface of the soil. The ultimate source of such waters is precipitation in the form of rain or snow upon the surface. Ground waters, however, have lost their identity as part of the surface runoff. The surface above them may be quite dry and the top soils contain but a limited quantity of moisture yet the subsoils may be completely saturated. This condition of moisture in the subsoils may not be due to percolation downward from the surface immediately above, but to waters which have found their way into them through subsurface flow or percolation. The source of ground waters may be far removed from the area upon which they are found at sufficient height to cause damage.

Where ground waters appear on the surface, as is frequently the case, the motion is an upward one. Such a condition indi-

cates that the subsoils have become filled, due to some underground discharge into them, and that the water table, due to such filling, has risen until it has reached the surface.

Drainage in the arid regions or on irrigated lands involves for the most part the removal of excess ground waters. The soil formation in those regions is generally of such character that water applied artificially or falling upon it in the form of rain is quickly absorbed. A large part of the water so absorbed is, however, retained in the subsoils. The presence and elevation of ground waters, except when they rise high enough to give surface indications of their presence, can only be determined by subsurface examinations.

It has been stated previously that ground waters do not differ greatly in character from surface waters; there is one exception to this which is frequently important. In their passage through subsurface strata they are brought into contact with larger quantities of soluble mineral salts than is the case with waters flowing over the surface. On this account they frequently carry large quantities of these salts in solution. Where the salts are of a character harmful to vegetation ground waters are sometimes unfit for irrigation purposes.

Movement of Surface and Ground Waters.—In the design of drainage works for the removal of either surface or ground waters attention must be given to their direction and in most instances to their rate of movement. Direction is necessary in order to determine where waters can best be intercepted by drains, and rate of movement to estimate the quantity that must be handled.

In dealing with surface waters their direction and rate of flow can be determined with a relatively high degree of certainty from topographic and hydrographic data. The direction of flow is dependent upon surface slopes and the amount upon the character and extent of the tributary area, and the amount of water which falls upon it in the form of rain or is applied to it by artificial means. All of these factors are in a large degree measurable quantities. The movement of ground waters presents a more difficult problem on account of the larger number of uncertain factors involved. The direction and rate of flow are both dependent to a large degree upon subsurface conditions. Ordinarily it is assumed that ground waters move with the slope of the country downward. This assumption is generally true when

applied to large areas such, for example, as extensive valleys or plains. It is not always true, however, when applied to small areas such as must ordinarily be dealt with in designing drainage works. Ground waters in their flow or percolation follow the more porous subsoil strata. The slopes of these strata may be irregular, and for small areas frequently do not correspond to surface slopes. A porous subsoil strata may be many feet deep at one place and but a few inches at another, or it may pinch out altogether. Conditions may be such as to form a basin filled with porous sands or gravels but without any marked underground outlet. Ground waters flowing into such a basin, if the quantity be large, may rise sufficiently to form surface streams or ponds. If the quantity be small they may find their way through the relatively tight materials surrounding the sand or gravel deposits. Ground water travelling through porous strata frequently finds its way to the surface along the foot of slopes where the porous strata are exposed. Below the slopes it may sink again into a porous subsoil, or it may continue as surface flow, depending upon the character of the materials encountered.

Ground water frequently exists under pressure due to the presence of semi-impermeable dikes or strata of hard pan or other tight materials. This condition of pressure may be due also to irregular slopes or contour, or a pinching out of the water-bearing strata. Good examples of the irregular contour of a porous or water-bearing strata are found frequently at the foot of slopes where old channels formerly cut in sand or gravel have become filled with non-porous materials. The water bearing stratum in this case is in the form of an inverted siphon, and the water passing through it is under pressure due to the head on the siphon. A porous stratum may terminate at or near the foot of a slope, the valley fill below being composed entirely of non-porous materials, here also water is under pressure due to the head in the porous strata above it.

Wherever ground water exists under pressure there is a tendency for it to be forced upward, through the more or less water-tight covering. The rate at which water will reach the surface due to this underground pressure is dependent upon the amount of head and the character of the material through which it must pass. Coverings of solid rock or hardpan or of indurated materials, if unfissured, will prevent the rise of water through them. So also may a heavy layer of the more impervious clay. Ex-

amples have been found where ground water, in sufficient quantities to create a seeped condition on the surface, had been forced upward through relatively tight materials from depths as great as thirty feet or more. Where the fill of fine earth material over a porous stratum does not exceed ten feet, water soon reaches the surface provided the pressure below is sufficient to carry it to that height.

The movement of ground waters, both as regards direction and rate, is governed by conditions of subsoil difficult to determine. Exact information regarding the character and relative positions of the various subsoil materials can only be obtained through exhaustive and careful subsurface investigations. Even with the most thorough investigation that it is feasible to make, many details relative to the character and variations in porosity of substrata can be approximated only. The presence of impervious dikes below the surface frequently cannot be determined except by their action in resisting percolation through them.

The difficulties and uncertainties of obtaining precise information relative to the subsurface formation of a dry soil, renders it impracticable in advance of the application of water to the surface, to foretell what the amount and action of ground waters will be. It is only by a study of the movement of the waters themselves that their direction and rate of motion can be determined definitely. The above condition makes it impracticable in most cases to plan drainage works for irrigated lands in advance of actual irrigation upon them. Even after irrigation has been begun several years may elapse before the subsoils become filled and the water table raised high enough to be detrimental to surface soils.

Changes in Elevation of Ground Water.—The average depth to water table over a given area depends upon the amount of the supply which the area received. The depth is subject to almost constant variation depending upon the distribution of the supply.

A heavy rainfall, lasting for a short period only, or the application of a large quantity of water to the land, may cause a rise in water table due to the fact that the water cannot drain out of the subsoil as rapidly as it is absorbed by it. So also a long dry period or lack of application of water to the surface may cause the water table to fall. A series of wet years may produce a corresponding period of high ground water over a large tributary

area. This may follow closely the period of excess precipitation or it may be some time, even years, before the supply reaches the area in question, depending upon the distance the underground supply must travel, and its rate of percolation through the subsoil.

Where the underground supply is fed entirely by direct precipitation or losses from natural streams, and is not increased nor diminished by artificial means, it may be assumed that equi-

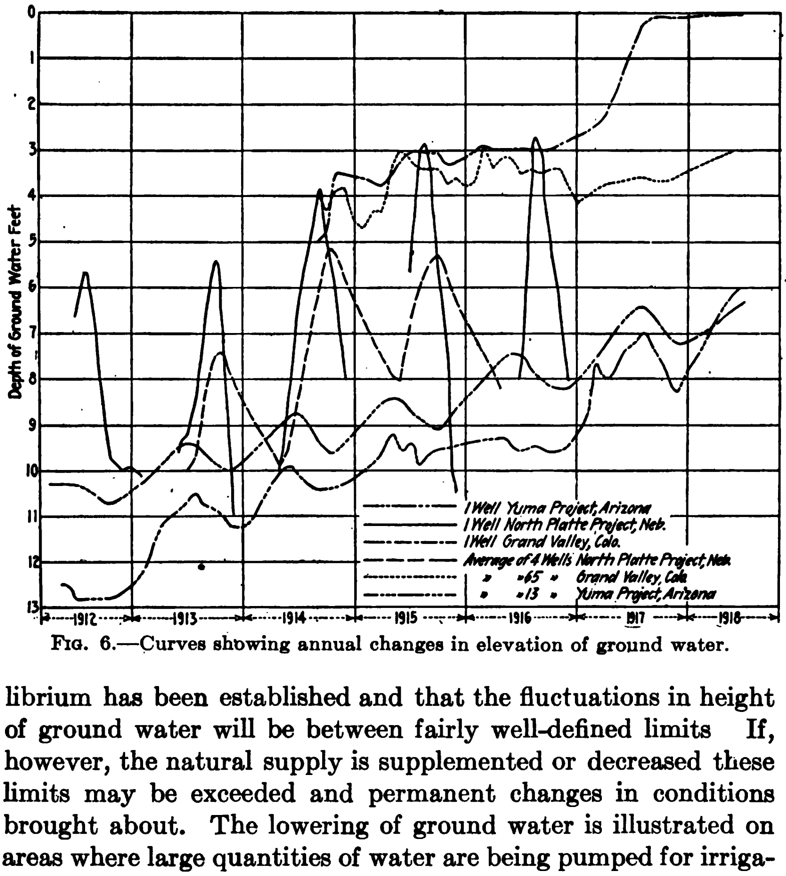

FIG. 6.—Curves showing annual changes in elevation of ground water.

librium has been established and that the fluctuations in height of ground water will be between fairly well-defined limits If, however, the natural supply is supplemented or decreased these limits may be exceeded and permanent changes in conditions brought about. The lowering of ground water is illustrated on areas where large quantities of water are being pumped for irrigation or other purposes. Observations made over a long period of time on such areas show that a general lowering of water table has taken place; Southern California where irrigation is practised extensively through pumping furnishes the best examples of such changes. Here a fall of from 50 to 100 feet in the elevation of

ground water since irrigation was begun is not uncommon and in many cases these figures are greatly exceeded.

In the arid valleys of the west, to which water has been diverted for irrigation, a premanent rise in ground water has resulted. On the North Platte Reclamation Project in Western Nebraska individual cases have been observed where the water table has risen as much as eighty feet during the past ten years, or since irrigation has been practised. In the Salt River Valley in Arizona the average rise in ground water, for a period of five years—1913 to 1918—as shown by observations on about 100 wells, was 7.5 feet or at the rate of 1.5 feet per year. Similar changes, but varying greatly in amount have taken place wherever large areas have been brought under irrigation. It is this change that makes drainage necessary for the protection of irrigated lands.

The rise in ground water on irrigated areas is frequently very erratic and generally show seasonal changes. In some cases the water table falls during the non-irrigating season well below the danger limit but rises the following season to a height as great or greater than that previously reached.

CHAPTER IV

FUNDAMENTAL FACTORS INVOLVED IN DRAINAGE

Natural and Artificial Drainage.—The term natural drainage is used to indicate the condition of lands in regard to permitting excess waters to escape from them. It is applied both to surface and to underground conditions and is dependent upon many and varying factors. Slopes, smoothness of surface and characters of soil are functions of the natural surface drainage. For the same character of surface, the velocity with which a given depth of water will flow over it will vary directly as some function of the slope. The amount of water which will be carried off an area without impounding deep enough to do damage will consequently vary as the slope of that area. If the surface of the land be rough or uneven, it offers resistance to flow over it.

Following a well-known law of hydraulics, the same quantity of water when confined in a channel will move with greater velocity than when spread out in a broad sheet. Examples illustrating this are numerous in broad flat valleys of reasonably moderate slopes where storm waters spread over large areas, and on account of their slow velocities cause the lands to be flooded. The same quantity of water if confined in a well defined channel of proper dimensions could be carried away quickly and without the overflow of adjacent lands. Good surface drainage may be defined as a condition that will permit the excess waters being carried away without impounding them to an extent that will do damage to the lands.

Natural underground drainage relates to the condition of soils and subsoils for carrying away waters that have been absorbed from the surface. Attention has already been called to the difference in character of the subsoils in the humid and arid regions. On account of the porous nature of the subsoils, underground drainage conditions are more favorable in the arid than in the humid regions. The result of this is that in the arid regions large quantities of water may, and frequently do, find their way downward through the porous subsoil formations and lose their identity so far as surface flow is concerned. Ultimately these

waters, or that portion of them which does not reach the surface by the slow process of capillary action and is there evaporated, must find their way to natural streams or lakes or in some cases to the ocean. The disappearance of streams, a common occurrence in the arid and semi-arid regions of the United States, is an example of underground drainage, and its effect upon surface flow. Numerous other examples are to be found below irrigated areas where the excess waters applied to the soils find their way to natural streams. In many cases the underground flow is over some impervious stratum and reaches the surface only where the stratum has been cut or worn away, as for example in stream channels or on the edge of cliffs or steep slopes. In the humid areas where the soils and subsoils are more tightly compacted, the drainage of excess waters is generally over the surface. Here the underground drainage is restricted on account of soil conditions. It is true, however, that all lands afford more or less underground drainage and that a part of the waters which reach the surface are disposed of in this manner.

Artificial Drainage.—Any work which facilitates the carrying away of excess waters may be regarded as artificial drainage. Such work may consist of preparing channels for removing flood waters from the surface or the construction of deep drains intended to carry excess water out of the soils. Artificial drainage may even consist of simply smoothing or removing obstructions from the surface so as to allow water to flow more freely over it. Another example is the enlarging of channels to sufficient size to carry flood discharge without overflowing adjacent lands.

As applied to soils and the improvement of their agricultural conditions, artificial drainage is intended to remove excess waters which collect on the surface or in the soils themselves. It includes also works which serve the purpose of deflecting or intercepting the flow of water onto lands. Drainage works for improving agricultural conditions may in a general way be divided into two classes. They are: first those intended to carry water from the lands directly and, second, those intended to prevent water reaching them either as surface flow or underground percolation. The first of these two classes is sometimes designated as relief and the second as intercepting drains. There is, however, no distinct line of demarcation between the two classes. All drains, if effective, serve, in a certain degree, to intercept water which otherwise would find its way to lower areas. They serve also,

in some degree, to carry water out of lands adjacent to them. The terms are convenient only for indicating the principal function which a drain is intended to serve.

When Artificial Drainage is Necessary.—From the previous discussion it may be seen that all lands are protected to a greater or lesser degree by natural drainage conditions. Were it not for this, large areas which are now under successful cultivation would be wholly unfit for agricultural purposes. The total amount of water which reaches the land is, in many cases, far in excess of that which can be used by plant growth. The excess above what can be used is carried away by evaporation from the surface and by natural drainage. It is thus that many soils are protected from becoming water-logged and unfit for growing crops.

In the processes of natural drainage the excess waters from the higher areas frequently drain onto the adjacent lower lands. This in many cases continues until the amount of water collected on the low areas is greater than their natural drainage capacity and they become seeped or overflowed. In this manner wet land valleys or swamps are formed. Frequently on account of their flatter slopes, or conditions of soil, the lower areas have less natural drainage than adjacent higher ones. This also contributes to their becoming too wet for use. The water-logging or flooding of lands in the manner above described is common both under conditions of natural rainfall, and where water is applied artificially in the form of irrigation. The same general principles apply to surface and ground waters, except that in the latter case the flow is below the surface and more difficult to determine.

Any excess of water, above what can be used by growing plants, or disposed of through natural drainage channels, may be regarded as detrimental to soils and should be removed by artificial drainage works. This applies equally to waters found upon the surface or within the soils themselves.

The needs for drainage works for removing surface waters are generally evident from surface conditions. In extreme cases lands are covered with water for all or a portion of the time, a condition which results in formation of swamps. From this extreme the amount of water varies to the point where transpiration of plants and natural drainage is sufficient to dispose of all waters which reach the soils. There is consequently a wide range in the requirements for artificial drainage. When soils

are completely saturated or covered with water sufficient to form a swampy condition drainage is necessary to reclaim and render them suitable for cultivation When the excess water in soils is but slightly greater than that which can be removed by natural drainage artificial works may be regarded as a means for benefiting soil conditions and increasing crop production. When an actual unwatering of lands is required, that is where soil is completely saturated or covered with water, the needs for drainage are at once apparent. When the excess of water is not great enough to completely saturate the soil the needs for drainage are more difficult to determine. A condition of saturation in the subsoil, if relatively near to the surface will reduce the volume of soil from which plant roots can obtain food and render their growth less vigorous. A high water table tends to increase the losses by capillary action and evaporation which may result in bringing alkali to the surface; it also prevents proper tilth in the soil.

In order to determine whether artificial drainage is necessary requires consideration of the character of the soil, the effect of water upon it, and also its moisture content under normal conditions. In heavy soils drains are sometimes necessary to increase percolation and induce a downward motion of the soil waters. This is especially true in humid areas where soils are underlaid by more or less impervious substrata If all excess water is carried away over the surface the soils become compacted and do not provide proper conditions for the nourishment and expansion of plant roots.

On irrigated lands the height of ground water relative to the surface is an indication of drainage requirements. A low water table indicates natural drainage conditions sufficient to carry away the excess waters which reach the subsoils; a high water table, on the other hand, indicates a lack of natural drainage sufficient for this purpose. When the water table rises sufficiently near to the surface there results a destruction of all useful vegetation. By systematic observations of the ground water elevations it is ordinarily possible to anticipate the needs of drainage sufficiently in advance to allow protective works to be constructed and prevent serious crop losses. It is impossible to lay down any fixed rule for the absolute danger limit in the heights of water table. This will vary with the character of soil and also the constancy with which the water table is held in one position.

The character of the water supply, that is, its freedom from harmful alkali salts in solution, is also an important factor.

Capillary Action.—The well known phenomenon of a liquid rising, against the force of gravity, in a fine tube or the minute pores of a body is known as capillary action. If a body containing fine tube-like pores or interstices be partly immersed in water, the water will fill the pores and rise in them above the free water surface. One of the most common examples of capillary action is that of a sponge, the structure of which is composed of hair-like fibers so close together that the spaces between them act the same as fine tubes in raising water. If a sponge be placed in a vessel containing a small quantity of water, the water will be carried upward by the attractive force of the sponge. Substances such, for example, as soft burned unglazed earthenware, coarse grained woods, porous rocks, and the various kinds of soils, together with a multitude of others, contain pores sufficient to draw water into them if brought into contact with it. Of the non-porous substances which do not exert capillary action may be mentioned rubber, glass and metals.

The force which causes a liquid to rise in capillary tubes, or in the fine pores between the particles of a solid, is that of cohesion or the attraction of particles of matter for each other. When this is applied to the surface of a liquid there results a phenomenon known as surface tension, by means of which capillary action may be explained. The mathematical laws which govern capillary forces and the heights to which a liquid will rise in pores of given dimensions is an interesting branch of Physics which cannot be discussed here. It is essential, however, that certain fundamental facts concerning it be clearly understood.

Capillary action takes place when the attractive force between the particles of the liquid and solid is greater than that between the particles of the liquid themselves. When this is the case the liquid tends to spread out in a thin film over the surface of the solid and cause it to become wet. This is the case when water is brought into contact with most solids. There are, however, some exceptions, if, for example, the surface of the solid is covered with a thin film of oil the particles of which are, in a sense, repellant to those of water, the latter if applied in limited quantities will not spread out over the entire surface but stand in drops. The same action is observed between mercury and

glass. These exceptions, while interesting in themselves, are not applicable to the action between water and the particles of which soil is ordinarily composed. It may be assumed that the force of attraction between soil and water particles is greater than that between the particles of water themselves. Were it not for this fact soils would not serve, in the same manner as they do, to carry a supply of moisture for plants.

One of the fundamental laws of capillary action is that the height to which a liquid will be lifted in a capillary tube varies inversely as the diameter of the tube. This same law applies also to the rise of water in the capillary spaces or pores between particles of soil. It is impractical, on account of the irregular size and shape of the pores in a soil, to determine a measure of its capillary action by calculation. It can be stated, however, that the smaller the pore spaces the greater such action will be. The size of the pores in a soil depends upon the size of the particles of which the soil is composed and also upon the degree of compacting to which it has been subjected. A finely divided soil will have a higher capillary action than a coarse grained one. The compacting action of water upon a soil tends to increase its capillary action.

The height to which water will be lifted in soils by capillary action depends upon so many varying factors that specific statements concerning it are likely to be misleading. It is impossible from an examination of a soil to determine with any degree of accuracy what its capillary action will be. The character and texture of different soils generally indicate whether such action will be high or low. Exact data for a particular soil, however, can be determined only by investigation and measurement.

Instances have been observed where water was lifted by capillary action, through from six to seven feet of soil, in sufficient quantities to cause the surface to be wet sufficiently to interfere with the growth of ordinary crops. Examples have also been found where free ground water at a depth of two and one-half feet caused no appreciable moisture on the surface and apparently did not interfere with the growth of shallow rooted plants. From these examples and from the records of other observations available, it seems probable that the maximum height through which water will be raised by capillary action in sufficient quantities to be harmful to soils and growing crops is about eight feet. The ultimate height to which capillary action may be felt is

undoubtedly much greater than that above stated; beyond this height, however, the quantity of water, generally, is so small that its effect may be considered negligible.

The condition of the top layer of soil has a marked effect upon the quantity of water which reaches the surface. A well mulched top soil or one composed of coarse sand or sandy loam will in a large measure prevent capillary action reaching the surface and reduce losses by evaporation. It is due to this fact that thorough cultivation serves to conserve the supply of moisture in soils.

Height of Water Table.—Reference has already been made to the zone of plant growth and attention called to the fact that the lower limit of this zone is frequently determined by the presence of free water in the subsoil. It is important on account of this condition that attention be given to the minimum depth, to ground water, necessary to maintain proper conditions for the growing of plants.

The water table must be low enough to provide the necessary soil above it for the support and nourishment of the plant roots and also to prevent harmful effects of excess capillary action to the surface. The latter is especially important in soils containing harmful alkali salts. Both of these requirements are of such character that no definite depth can be fixed which will apply to all conditions. Some plants are shallow rooted and can use only a limited depth of soil for their subsistence and growth. Others are naturally deep rooted and require a deep soil for their best growth and development. It is well known, also, that plants will accommodate themselves, in a large measure, to soil conditions. This is especially true of deep rooted plants, which if grown on shallow soils will develop a root system suitable to those soils. Alfalfa ordinarily sends a main or tap root to a depth of several feet below the surface; if, however, the depth of soil is limited by the presence of a high water table or by an impervious subsoil the deep tap root is absent and the plant is nourished by a system of shallow lateral roots. This changed condition restricts the expansion of the root system and lessens the available food supply. The plant is consequently less vigorous and its life less enduring. In determining the minimum depth of water table that may be allowed without detrimental effect upon growing plants the character of plant must be considered. For general agricultural purposes a zone

of plant growth sufficient for the deep rooted plants must be provided. Just how much this shall be is a question upon which no definite agreement has been reached by different investigators. Experience seems to show that for general farming purposes a depth of from five to six feet of unsaturated soil is ordinarily sufficient for the expansion and growth of the root system.

The constancy of the height of water table is also important in maintaining proper conditions for plant growth. If the height of the water table is variable the plant roots which expand downward during the low stages are injured or destroyed when the ground water rises over them. The harmful effects of a variable water table can be overcome, in a great measure at least, by providing drainage works sufficient to keep the ground water, at all times, below the minimum required. This leaves a zone of plant growth sufficient to sustain the plant even though its deeper roots are destroyed.

The depth that ground water must be maintained in order to protect the top soils from the harmful effects of alkali salts depends largely upon the capillary action of the soils. If water containing salts in solution is carried to the surface by capillarity and there evaporated the salts will be left on the surface. The remedy for this is to keep ground water at a sufficient depth to prevent an appreciable quantity reaching the surface by capillary action. Soils in condition for growing crops, and when properly cultivated, have a relatively low capillary action; seldom exceeding three or four feet. A depth of water table sufficient to provide for the growing of ordinary crops is generally sufficient to protect the top soils from harmful effects of alkali brought up by capillary action. That is, provided thorough cultivation is practiced. In soils that are highly alkaline, the result of long and continued seepage, capillary action is high. The reclamation of such soils by drainage is expedited by lowering the water table to a somewhat greater depth than the figures above given. This extra depth will more effectively cut off capillary action and hasten the drying of the surface sufficient to allow cultivation to be begun. On some of the irrigated areas of Egypt, all lands are cultivated whether cropped or not. This is to keep the surface mulched and prevent the rise of alkali through capillary action.

Surface and Subsurface Drains.—In accordance with the purpose they are intended to serve, drains are frequently classi-

fied as surface and subsurface. The former, as the name implies, are those intended to carry water from the surface, while the latter are those intended to remove water from the soil.

The character of soils to be drained determines, in a large measure, whether drains shall be of the surface or subsurface type. In tight soils which are underlaid by more or less impervious subsoils, surface drains ordinarily will serve to remove the excess waters which reach them. Subsurface drains are, however, frequently used in soils of this type, and when so used serve the purpose of inducing a downward motion of water through the soils. This, as will be seen later, is one of the advantages of drainage works. In soils which are underlaid by porous subsoils, which readily become filled with ground water, subsurface drains are necessary to carry away the excess from the subsoils and prevent the water table rising too near to the surface.

On account of fundamental differences in soils and character of water supply, surface drains are more commonly used in the humid areas while subsurface ones generally are better adapted and necessary to removing excess waters from irrigation. The locations of surface drains are determined chiefly from surface topography; generally that location being chosen which gives the most practicable line at least cost of construction. This is usually in the lowest portion of the area to be drained. The location of subsurface drains, to be effective, must be determined from subsurface conditions, both as regards porosity of soils and elevation of ground water. On account of these conditions such drains frequently must be located at variance with natural drainage channels.

Effects of Drainage on Soils.—In planning drainage works their various effects must be considered in order to determine whether the desired results can be accomplished. The primary purpose of drainage is to improve soil conditions and a clear understanding must be had of what these improvements are to consist of, and how they are to be accomplished, before the work can be considered feasible.

The principal direct effects of drainage works are, first—to carry away surface waters where these stand or flow over the surface, and second—to draw ground waters out of the soils and subsoils. There are other indirect effects such, for example, as increasing porosity, areating and improving tilth, and the washing out of impurities. These changes are all beneficial to soils.

It is important first to determine whether soils are injured by the presence of excess water, and if so, can this condition be remedied by the construction of drainage works. To answer these questions may and frequently does require an investigation of the physical character and water content of the soil. In many instances the condition of soils as regards moisture is sufficient to determine their drainage requirements.

It is well known that the presence of free water on the surface for a longer period than is necessary for soil to absorb the required amount of moisture is detrimental both to the soil and to growing plants. This applies equally to lands supplied by natural rainfall or artificial irrigation. In the former case the amount of water supplied cannot be controlled and drainage is necessary to dispose of the excess. Conditions of this kind are common in areas where rainfall furnishes more water than soils can absorb and use. The general effect of drains under the above conditions is to protect lands from being submerged and soils from becoming water-logged.

In localities of heavy rainfall and steep slopes, water may flow over the surface with such velocity and in such quantity as to carry away the soil, and also cause damage to growing crops. It is possible by means of drains, properly located and constructed, to intercept the flow over the surface, and carry it away in such a manner as to reduce, if not wholly prevent, erosion of the soil. Such drains by their action in carrying away surface waters at a rapid rate, may prevent the necessary amount being absorbed to render the soils moist. This generally can be avoided by furrowing, or roughening, so as to impede the flow of the water on the surface of the soil. The construction of closed drains in such manner as to cause water to percolate through the soil before entering them may also increase absorption.

On irrigated lands artificial drainage works which serve the purpose of carrying away excessive irrigation wastes, contribute also to a leaching of the soils which, in time, may become detrimental. Where natural drainage is sufficient to take care of reasonable irrigation wastes, effort should be made to reduce the amount of water applied to the land rather than to construct drainage works. Where it is possible to keep excess water from entering the soil consideration should be given to this plan as an alternative to providing drains for drawing water out of the soil.

CHAPTER V

BENEFITS OF DRAINAGE

Removal of Excess Waters.—In determining the benefits that may be derived from the proper drainage of soils, various physical factors and changes must be considered. In one sense it may be said that the removal of excess water is the only beneficial effect that drainage may be expected to accomplish. There are, however, physical changes of the soil brought about through drainage which are decidedly beneficial, and on this account deserving of mention.

One of the essential requirements for plant growth is water. Equally important to supplying the necessary water for a plant's existence is protecting it from excess quantities which would prevent its growth. The amount of water necessary for plant growth depends upon the character of plant and the climatic conditions under which it exists. Generally plants of rapid growth require more water than those of slow growth. Other conditions being the same the rate of growth for a given plant ordinarily depends upon the amount of water available for it in the soil, until a certain maximum is reached. Beyond this, additional water not only does not increase the growth of the plant but, on the contrary, tends to impede it. The maximum requirement for a plant is what has been referred to as the optimum water content of the soil. Theoretically at least, ideal conditions would be produced if this optimum amount could be maintained constantly in the soils. It is evident, however, that such a condition cannot exist under intermittent and irregular rainfall. Neither is it possible under present systems of periodic deliveries as practiced in irrigation.

It matters not whether water falls as rain, or whether it is applied artificially by irrigation, the top soils are generally saturated for a greater or less period of time while receiving a supply. How long this condition of saturation may last depends upon the amount of water reaching the soil, and also upon the latter's power of absorbing or otherwise disposing of the excess. In other words, upon natural drainage conditions in the soil.

The amount of water falling during a single storm, or that applied at one irrigation, may be sufficient to fill all pore spaces, and cause a condition of saturation in the soil to the depth that plant roots ordinarily will penetrate. When this occurs the free water must drain out before the soil is in proper condition for plant growth. When soils are porous and natural drainage conditions provide an adequate outlet, the free water which fills the pore spaces will soon be carried downward by the action of gravity, and only capillary water, which is available for use of plants, will remain. This downward motion, which is necessary to prevent continued saturation in the soil, may be obstructed by the presence of non-porous strata or by the subsoils being filled with water.

Drainage serves to remove the excess water which finds its way into the soil before it does appreciable damage to growing plants. The action of drains is not confined to the periods when water reaches the soil through rainfall or irrigation. Drains when properly located, and constructed to adequate depths, serve almost continuously in drawing water from the soil. By this constant action the ground water may be kept well below the surface and, to some degree, storage capacity provided in the subsoils, which will allow excess waters from the top soil to move downward. On thoroughly drained lands the excess or free water moves quickly out of the zone of plant growth and produces a condition favorable to the growing of plants within a minimum time after water has been applied to the surface. The soil is thus protected from remaining in a saturated condition long enough to cause a suspension of plant growth.

The beneficial effects of removing excess waters from the surface are in some cases equally important to drawing them out of the soils. In regions of heavy rainfall, and especially where the soil is relatively tight and underlaid at shallow depths by impervious material, surface flooding frequently occurs. In such cases it is sometimes practicable to dispose of the greater part of the excess waters over the surface and before the soils become fully saturated. To accomplish this provision should be made for collecting surface waters by means of shallow drains and discharging them into outlets of adequate capacity. On heavy non-porous lands drainage works of this sort may be made effective for removing a large part of the excess waters even before they are absorbed by the soil. In regions of heavy

rainfall this method is sometimes the most economic one on account of the large amount of water that must be carried away. The drainage of all excess water from the surface, however, tends to compact the top soil, and also prevents the beneficial effects of a downward motion of water through it.

Increasing Porosity in Tight Soils.—One of the requirements of soils, as has been mentioned, is porosity. In order that plants may grow successfully in a soil, it must be in a condition that will allow roots to penetrate it freely and thus obtain the necessary supply of food and moisture. Porosity is also necessary to allow water and air to penetrate and move through the soil. When the spaces between the soil particles are of dimensions comparable to fine capillary tubes they offer a high resistance to the movement of water through them. A finer-grained soil, consequently, absorbs water slowly, but when once wet, holds its supply with great tenacity against the action of gravity. Capillary action also plays an important part in tight soils. It is frequently sufficient to cause an entire filling of the pore spaces to a considerable height above free ground water. The power of tight soils to hold water decreases the effectiveness of drains in them and increases the time necessary to remove excess waters.

The porosity of a soil as heretofore stated depends upon the size and graduation of its particles and also upon the degree of compacting to which it has been subjected. There are, however, certain natural agencies which tend to increase porosity of tight soils. These are the growth of plant roots, the drying out of the soil, and, in many cases, the downward motion of water through them. Artificial means that are frequently adopted are the mechanical breaking up of the soils and subsoils by deep cultivation or the use of explosives, and by chemical treatment. Certain substances, such for example as lime, gypsum and sulphuric acid, tend to modify the physical condition of a soil in such manner as to allow water to pass more readily through it. This effect is probably partly mechanical, in rearranging the particles, and partly chemical in breaking up the elements of which the soil is composed.

Drainage increases the porosity of a tight soil, first—by providing an outlet for the excess waters and, second—by extending the depth of the zone of plant growth. The presence of a high water table prevents a downward motion through the soil, and causes the lower strata to remain in a saturated condition. Sur-

face waters can find little or no outlet downward through the soil and must be disposed of as surface flow, or by evaporation. Drainage carries the excess water out of the subsoil and permits a downward motion of that held in the soil above. It reduces the height to which water is held by capillary action by lowering the underground reservoir or supply. The downward motion of water opens the pore spaces and causes air to be drawn into them. By carrying away the free water from the soils and lowering the water table a condition is created whereby plant roots can penetrate to a greater depth. This further increases the pore spaces and also increases the content of organic matter.

When a soil is underlaid by an impervious stratum or hardpan, through which water cannot penetrate, the cutting of drains into the hardpan at frequent intervals will remove the excess water which collects on the top of it. This also gives a free outlet for the soil above and tends to produce a downward motion of water through it. It also creates a condition whereby the top portion of the hard stratum is gradually broken up by the disintegrating effects of air, and the growth of plant roots into it.

Conservation of Water Supply.—The quantity of water that can be beneficially used by plants depends upon the amount retained by soils in a condition available for the roots to absorb it. If the amount of water held by the soil is too small, that is below the wilting content, not enough can be absorbed by plants for their continued existence. Where the water content in the soil is too large as, for example, where the soil pores are completely or nearly filled, plants are also unable to absorb water from it. It follows that water may exist in a soil and still be of no value for growing useful plants. Where such is the case that portion of the supply which cannot be used may be considered as wasted. To illustrate—we will consider the case of water being applied to a soil at regular intervals, but in such limited quantities that the soil would not be rendered sufficiently moist to support plant growth. The entire supply under such conditions would be wasted so far as useful results are concerned. Again consider the case where water is supplied in such quantities that the soil is kept continuously saturated, useful plants cannot survive generally in this soil, and the water applied to it also is wasted.

In regions where water for agricultural purposes is limited, either on account of small rainfall or insufficiency of an irrigation supply, it is necessary to conserve it, in so far as possible, in a condition available for the use of plants. It has heretofore been stated

that soils of fine texture when in a loose friable condition have a greater pore space and also a greater capacity for capillary water, which is available for plant growth, than soils of coarse and varying texture. When soils are compacted, as is the case in a water-logged condition, the total pore space is reduced on account of the particles being more nearly in contact with each other.

The total volume of the pore spaces and consequently their capacity for holding water is increased by drainage. Water when applied to a tight soil tends to fill the pore spaces and assume a condition in which it is not available for plant growth. There is a consequent waste of the excess water through evaporation or underground losses before the soil is restored to a proper condition for plants to grow in it. Loosening of the soil increases its capacity for holding water without its becoming saturated. The result is that greater conservation of water can be accomplished in a well-drained soil, than in one not so drained.

Reclamation and Protection from Alkali.—Reference has frequently been made, in the preceding pages, of soils becoming injured and unfit for cultivation through the accumulation of harmful alkali salts at or near the surface. Conditions of this kind are found in the arid and semi-arid regions where soils contain more or less harmful salts. It is recognized that drainage provides the only efficient and practical means whereby such soils can be reclaimed and protected.

The injurious effect of alkali is frequently, but not always, the result of its accumulation in the upper portion of the soil through irrigation. In some instances, as heretofore mentioned, alkali has been deposited through natural processes in sufficient quantities to render soils unfit for use. Such soils are generally considered as having no agricultural value, until the excess of salts which they contain have been removed. The greatest damage due to alkali generally results from the depreciation of soils that have been brought into successful cultivation through irrigation upon them.

Drainage on irrigated lands may be regarded first, as a means of relieving them from excess quantities of alkali, already accumulated, and, second—as a protection against accumulations due to irrigation. The effects of drains are first, to cause a lowering of the water table and produce a downward motion of soil waters; and second, to prevent or retard capillary action and the consequent upward motion of alkali to the surface. The first of these may be considered as remedial, and the second

FIG. A.—An alfalfa field converted into an alkali flat due to high ground water—Wyoming.

FIG. B.—Sugar beets growing on reclaimed seeped land. North Platte Project, Nebraska.

(Facing Page 50)

PLATE V

FIG. C.—An abandoned ranch, the result of excess ground water and alkali Colorado.

FIG. D.—Plowing and seeding reclaimed swamp land—California.

protective. The two functions, however, are not distinctly separate since conditions which serve to remove alkali already accumulated in the soil serve also to prevent its accumulation. The converse of this is only partially true, and it is sometimes necessary, for lands badly alkaline, to construct more extensive works for their reclamation than would have been required for their protection, had such protection been provided before serious injury had occurred through alkali accumulations.

The amount of alkali which drains will remove depends upon its concentration and the amount of leaching to which the soil is subjected. The latter varies with the amount of the drainage discharge. Waters discharged by drains have in exceptional cases been found to carry as high as 7 per cent. of salts in solution. These were the results of surface deposits which when dissolved by storm water or by artificial flooding found free access into the drains. The results of alkali determinations in drainage waters show that they carry the maximum when drains are first constructed, and that the quantity decreases as their operation continues. Near Huntley, Montana, the water discharged by newly constructed drains contained, in some instances, from 2 to 3 per cent. of dissolved salts. After a few months operation of the drains this quantity, generally had fallen to less than one-half of one per cent.

A convenient method of expressing quantities of alkali discharged by drains is in tons per acre feet of water discharged. These quantities for percentages varying from 0.1 to 1.0 are as follows:

Percentage of salts in solution	Tons of salt per acre foot of water
0.1	1.361
0.2	2.722
0.3	4.083
0.4	5.444
0.5	6.805
0.6	8.166
0.7	9.527
0.8	10.888
0.9	12.249
1.0	13.610

From these relations the quantities for any given percentage are easily calculated.

The following table contains data relative to discharge and quantity of alkali removed by drains on the Huntley project, Montana, U. S. Reclamation Service, for the years 1914 and 1915.

TABLE 2.—DISCHARGE OF DRAINS AND QUANTITIES OF SALTS REMOVED FOR THE YEARS 1914 AND 1915
(Huntley Project, Montana)

Drain no.	Length, miles	Average discharge, second feet	Quantity of water removed, acre feet	Per cent. of soluble salts	Tons of salt removed
1914					
2	1.04	0.48	347	0.120	567
5	1.51	0.44	315	0.195	836
5–1	....	0.06	47	0.100	64
6	3.30	1.45	1049	0.180	2571
7	2.19	0.75	543	0.265	1958
8	1.02	0.24	172	0.059	138
9	1.96	0.49	354	0.650	3131
10	4.22	1.07	770	0.230	2410
11	....	0.35	252	0.070	240
12	....	0.25	186	0.140	354
14	....	0.15	108	0.160	235
17	....	0.16	117	0.170	271
	(15.24)	(4.92) 5.89	(3550) 4260		(11,611) 12,775
1915					
2	1.04	0.66	477	0.075	486
5	1.51	0.39	282	0.180	691
5–1	1.17	0.28	204	0.090	250
6	3.30	1.15	830	0.150	1694
7	2.19	0.80	577	0.180	1414
8	1.02	0.31	223	0.050	152
9	2.55	0.60	431	0.285	1672
10	4.76	1.06	768	0.165	1725
11	2.18	0.71	514	0.065	455
12	1.87	0.90	650	0.105	929
13	....	0.54	390	0.520	2760
14	1.17	0.30	214	0.160	466
17	2.84	1.04	749	0.135	1376
	(25.60)	(8.20) 8.74	(5919) 6309		(11,310) 14,070

Lengths given are for drains completed and in operation for entire year. The totals shown in parenthesis ( ) are for drains for which lengths are given.

Quantities of salt removed per year per mile of completed drains amount to 762 tons for 1914 and 442 tons for 1915.

Quantities of salt removed by one second-foot average discharge per year amounted to 2169 tons for 1914 and 1610 tons for 1915.

Average salt content in drainage waters was approximately 3 tons per acre foot, or 0.22 per cent. for 1914 and 2.4 tons per acre foot or 0.175 per cent. for 1915.

These data show in every case a lower salt content in the water for 1915 than for the previous year, which indicates a gradual decrease of alkali in the soils. The area tributary to the drains given in the table could not be determined with any degree of accuracy; it is on this account impossible to give positive figures relative to amount of alkali salts removed per acre. It is estimated that the area affected by drains did not exceed 8000 acres during 1914 and 12,000 acres during 1915. On this assumption the quantity of salts removed amounted to about 1.6 tons per acre for 1914 and 1.2 tons per acre for 1915.

Table 3 gives similar data for Shoshone project, Wyoming, for the year 1914. In this case the salt content in the water was determined from composite samples, prepared by taking samples from each drain at or about the same time and mixing them in amounts proportional to the quantities discharged by the different drains. The first samples taken in April were used for computing the salt content from January to April inclusive. For the remainder of the year, samples taken at monthly intervals were used.

Table 3.—Discharge of Drains and Quantities of Salts Removed for the Year 1914

(Shoshone Project, Wyoming)

Month	Quantity of water discharged, acre feet	Per cent. of salts in solution	Tons of salts removed
Jan.-April	1,760	0.14	3,353
May	1,044	0.13	1,847
June	1,781	0.14	3,393
July	1,901	0.16	4,140
August	1,942	0.14	3,699
Sept.	1,730	0.10	2,354
Oct.	1,561	0.11	2,337
Nov.	1,137	0.12	1,857
Dec.	842	0.12	1,375
	13,698		24,355

Aeration of Soils.—The drawing out of water and increasing the volume of pore spaces, increases the amount of air, and other gases in the soil. Whatever volume of water is removed an equal volume of air is immediately drawn in to take its place. So also when the particles of soil are further separated, and

interstices increased, additional air is required to fill them. Drainage as a result increases the quantity of air and also creates more favorable conditions for its circulation through the soil.

The presence of air containing, as it does, various gases produces both chemical and physical changes that are beneficial to soils and also to plant growth. It is through chemical action that the various constituents are broken down and converted into forms available for the use of plants. Air is one of the necessary factors in the decay of organic matter. Without it vegetable matter, which plays such an important part in rendering soils fertile and friable, would remain, for a long period at least, in a condition of little or no value as plant food. Examples of undecayed vegetable matter are common in swamps and marsh lands where the air is excluded by the presence of water in the soil. It is due to the fact that air is excluded from it that wood does not decay when continually immersed in water. Air is also necessary for the growth of plants. It is absorbed both by the roots and the leaves. The best conditions for growth require that the soil be maintained in a condition which will allow free circulation of air through it.

Warming of Soils Through Drainage.—An undrained soil is generally a cold soil. Experience has shown, other conditions being similar, that a thoroughly drained soil is warmed more rapidly, and that crops may be started upon it earlier in spring time, than is the case where drainage is lacking. That a light sand or sandy loam will become warmed sufficiently to germinate seeds more quickly than a heavy clay soil, is well known to those who have had experience in agricultural operations. This difference is due largely, if not wholly, to the better natural drainage conditions and consequent smaller water content ordinarily found in the light sand or loam soils. It matters not whether drainage is the result of natural conditions or whether it is brought about through artificial means, the lowering of its water content in any manner renders the soil more susceptible to the heating effects of the sun's rays, and a soil when completely saturated will be warmed more slowly than when its pores are only partially filled with water.

In order to present clearly the effect of drainage upon soil temperatures, it is necessary to refer to the properties of different bodies for absorbing and transmitting heat. It is well known

that the amount of heat required to raise the temperature of a given mass through a fixed number of degrees varies greatly for different substances. In other words some substances have greater power of absorbing heat for the same change in temperature than others. The amount of heat that a substance will absorb for a given rise in temperature, or what is the same thing the amount of heat required to raise its temperature by a given amount, is termed its thermal capacity or specific heat. The latter term is the one ordinarily used for practical purposes. It is defined as the amount of heat required to raise unit mass of a substance through one degree.

Of all substances ordinarily met with in nature, water has the highest specific heat. It is roughly about five times that of ordinary soil, that is the amount of heat required to raise the temperature of a given mass of water through one degree would raise that of an equal mass of soil through about five degrees. From this the effect of excess water upon temperature changes in a soil is readily seen. The high specific heat of water is probably the greatest factor in retarding the rise in temperature of a wet soil in spring time. It is not, however, the sole cause. The fact that heat will not readily pass downward through water also has an important effect upon the rise in temperature in a wet soil.

It is well known that some substances, especially the metals, conduct heat rapidly, while others, of which water is a notable example, conduct it slowly. The measure of the power of a substance to conduct or transmit heat through it is termed its conductivity. Water has a low conductivity, and the distribution of heat through it would scarcely take place were it not for what is termed convection currents. These are simply the moving of heated portions of the water in the form of currents. Water when heated above its temperature of maximum density 39°F. expands in volume and its density decreases. If heat be applied to a vessel containing water, that portion of the water in contact with the bottom and sides of the vessel will upon becoming heated expand and rise to the surface. The colder water above on account of its greater density will descend and take its place. Through the movement of particles upward, heat is conveyed from the bottom and walls of the vessel and gradually distributed to the entire mass of water until the boiling temperature is reached. If the application of heat be further continued the particles in contact with the walls of the vessel will be con-

verted into steam and in this form rise to the surface and escape. Warm water, on account of its lesser density, always tends to move upward. If heat be applied to the surface the top portion will only become heated due to the fact that hot water will not move downward. The temperature of the surface of a lake or pond when exposed to a hot sun may rise several degrees without producing any change a short distance below the surface.

The application of the above principles to a soil saturated with water is apparent. The amount of heat required to warm it is greatly in excess of that required for a dry or moist soil. The presence of water retards the absorption of heat by the soil on account of its low conductivity, and the fact that surface water when warmed will not move downward and impart its heat to the deeper soil strata.

CHAPTER VI

DRAINAGE INVESTIGATIONS

Necessity for Investigations.—One of the essential requirements for planning drainage works is an intimate knowledge of the area to be drained. It has been seen from previous chapters that drainage has a marked influence upon the physical condition of soils; this must be taken into account in determining the beneficial results which may be expected. The proper location and correct design, for drainage works, require a knowledge of the character of soil and its condition so far as water content is concerned. They require also, a knowledge of topography and the source and direction of movement, if any, of the waters to be removed.

In general, it may be assumed, that the carrying out of excess, or free water, is beneficial. This is due to physical changes which are produced in the soil and also to the fact that a water content in excess of the optimum amount is detrimental to plant growth. In order that drains may be so located and constructed that they will be efficient, and that beneficial results will follow, a clear understanding must be had of present conditions and how these conditions will be modified when drains are in operation. It can not be assumed that the building of drainage works will have an effect, beneficial or otherwise, unless such works are capable of producing changes in the physical conditions or water content of the soil.

In many instances, investigations and study are required to determine whether artificial drainage is really necessary, or whether the required changes in soil conditions can be brought about more readily through other means. Examples are frequently found in irrigated areas, where the seepage and waterlogging of lands are caused directly by over irrigation or from canal or lateral losses. Better practice in the application of water or the water-proofing of canals and laterals may in such cases prove equally effective and less costly than the construction of drainage works. It must not, however, be assumed, that these remedies are applicable or that they can be made effective

in every instance where seepage results from excess irrigation or from canal and lateral losses. Each case depends upon local conditions involved, and requires special consideration.

In humid regions it is frequently a question of importance whether wet and water-logged areas should be relieved by direct drainage over them or by diverting flood waters the accumulations of which may be the real source of damage. The entire amount of a water supply may not be in excess of that required by soils for the best agricultural results but artificial works may be necessary to distribute this supply and to prevent portions of the lands receiving more and others less than the required amount of water.

In most cases the need for drainage is readily determined. Any considerable quantity of excess water in a soil soon renders it unfit for profitable cultivation. The important questions generally are whether drainage can be successfully accomplished and soils brought to a condition suitable for growing crops; and, if so, in what manner. The one extreme to be dealt with is the case of soils which are of no value until reclaimed by artificial drainage; the other that where drainage will slightly improve conditions and increase crop yields. Between these many intermediate stages may be found. Wherever drainage is contemplated, either for the purpose of wholly reclaiming soils or for increasing their productivity the economic features must be considered. It is clear that a drainage enterprise, for agricultural purposes, to be economically a success must show values in the way of land improvements more than equal to its cost. Before sound conclusions can be reached and the feasibility of a project determined careful investigations and study must be made of its physical and engineering features.

Importance of Reliable Data.—Data to be used as a basis for planning drainage works must be reliable and accurate. Especial attention must be given to collecting such data as will have a direct bearing upon the problems to be solved. Miscellaneous and general information relative to soils and ground water conditions are not sufficient for the engineer who is charged with the responsibility of laying out and constructing an efficient and economic system.

Instrumental data, such, for example, as determining locations and elevations, it is assumed will be checked sufficiently to eliminate errors.

Data regarding water supply, soil and ground water conditions should be collected with the same care with which instrumental observations are made. It is important, also, that data be sufficiently comprehensive and exhaustive, to permit of accurate deductions being made from them. It must be remembered, in dealing with soils and soil waters, general conclusions must be reached from relatively few and possibly, in some instances, from isolated observations. If accurate conclusions are to be reached the data upon which they are based must be accurate. A greater number of independent observations is required to determine the exact character of a complex soil structure than of a simple one. The same is true also of a varying or irregular water table. The collection of reliable drainage data requires accuracy, careful observation and judgment. For best results, it should be under the supervision of an engineer of training and experience in that particular line of work.

Character of Data Required.—The engineering information necessary for a consideration of a drainage problem may be classified ordinarily as surface and subsurface. The former refers primarily to topography, surface water supply, and outlet conditions. In some instances, especially in the humid regions, surface data is all that need be considered. Generally in such cases the impervious character of the lower soil strata prevents water entering or passing through them and drainage consists in removing the excess which collects on the surface. Even in these cases it is sometimes necessary to investigate the character and depth of top soils in order to determine the proper depth of drains.

Subsurface data refers primarily to character of soils, and subsoils, the elevations and fluctuations of ground water and the grades or slopes of water table. These data are necessary to determine where ground waters may be tapped and removed. They are essential too, in determining, in advance of construction, the probable effect of drains and in estimating the amount of water that must be removed. The character of materials determines largely the rate at which water may reach drains, and, in one sense, is comparable to grades or slopes in the movement of water over the surface. The elevations and fluctuations of ground water show areas that are damaged or liable to damage due to high water table. The slopes of water tables indicate the direction of movements of ground waters and, when carried far

enough, the locations of sources from which seepage supplies are travelling.

Surveys.—The surveys necessary for drainage investigations may be classed as topographic, soil or subsurface and hydrographic. A knowledge of topographic conditions sufficient to determine whethei necessary slopes and outlets are available should be first obtained. It is sometimes necessary to carry on preliminary investigations to obtain this information, and where necessary, this should be done, before deciding that a proposition is worthy of detail investigation and study. Ordinarily sufficient data, to determine whether slopes and outlet conditions are such as to make drainage possible, can be obtained without making extensive surveys. Assuming that these are favorable a topographic survey, as a rule, should be the next work to be undertaken, although in some instances, especially on irrigated lands, soil or subsurface surveys may be carried on at the same time with some saving of cost. Generally the most convenient form of topography is an accurately prepared contour map. Such a map is of especial value where the location of drains is controlled wholly or in a large part by surface conditions as is often the case in main outlets and where surface water only is to be removed.

Where locations are governed by soil or subsurface conditions, as is generally the case on irrigated lands, they must be based upon investigations of these conditions. Even in these cases the contour map is of value in expediting the work. The cost of preparing a contour map where a comprehensive drainage system is required is generally far less than the saving that can be effected by its use in laying out and constructing the works. Contour maps are useful in a variety of ways in connection with agricultural lands, a fact, which also should be considered. The detail character of maps, as for example, scale and contour interval may vary for different conditions and character of work for which intended. No specific rules can be laid down governing the exact kind of map that should be prepared for a particular case. The engineer should decide before beginning work what detail information is required and maps should be prepared so as to show this clearly.

Very flat but irregular slopes are sometimes found, where a contour interval of but one foot is scarcely small enough to show all necessary detail, in other cases an interval of five feet is not

too large. In general, a small scale has an advantage over a large one provided the necessary detail can be shown in a legible manner. The advantage of the smaller scale is that it permits of a larger area being brought under the eye at one time than is the case where a large scale is used.

The work of taking topography and preparing contour maps for drainage is the same as for other purposes. Since the question of topographic mapping is fully treated in various text books it is deemed unnecessary that it be discussed here.

Subsurface Surveys.—Investigations to determine the character of soils and subsoils and elevations of ground water are made by means of borings or test pits, a record, or log, being kept of the different strata encountered. In soils that can be readily penetrated by an auger and which will adhere to it, sufficiently to permit samples being brought to the surface, a satisfactory examination can be made from borings. Ordinarily this method can be used in materials that contain a sufficient amount of clay to render it adhesive. For sands which will not adhere to an auger, and for coarse gravel, or other materials containing rock so that an auger will not penetrate them, the use of test pits is generally necessary. Where material is very fine and saturated with water cribbing is sometimes required to keep a test pit open. It is sometimes possible to bore through light sandy loams or even sand by using a casing, slightly larger than the auger, to prevent the hole closing up and allow samples to be brought to the surface.

In making subsurface investigations special attention must be given to porosity or water carrying capacity of the materials encountered. This, as has been stated already, depends largely upon the relative amounts of different sized particles of which the soil is composed. An idea of porosity may be obtained by mechanical analysis, that is by separating the various sized grains of which the soil is composed. Generally, however, this is not necessary, as distinctly porous or water carrying materials are easily recognized. Extreme care is sometimes necessary, however, to detect the presence of thin strata of sand or planes of contact between different materials. These, in many cases, are capable of carrying large quantities of seepage water.

For the purpose of keeping a clear record of underground conditions the various strata must be classified and their positions

and thicknesses noted. Some such form as shown in Fig. 7 may be used for this purpose. It must be understood that the terms used are more or less arbitrary and that in many cases there is no sharp line of demarkation between the different materials. This makes it necessary to exercise care in order to maintain consistency in classification. The primary requirement

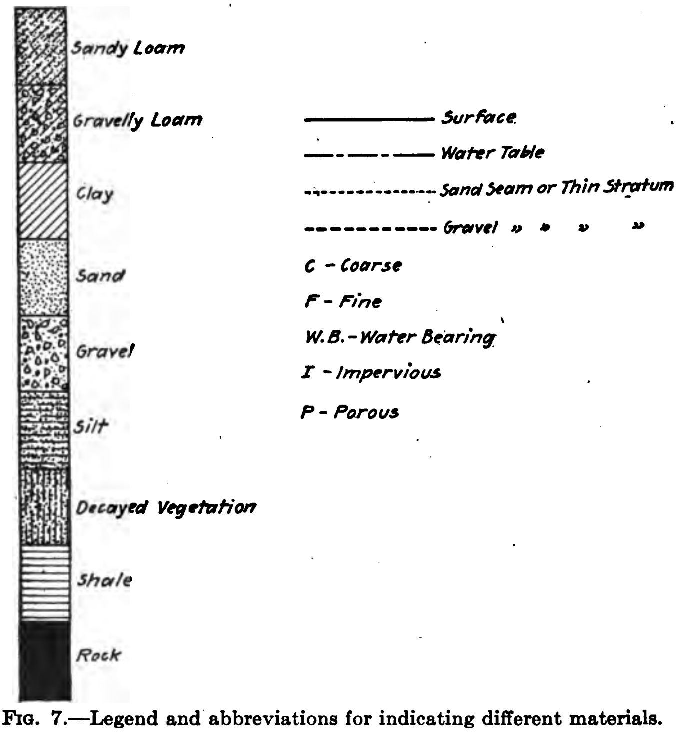

FIG. 7.—Legend and abbreviations for indicating different materials.

is to determine whether the subsoil is sufficiently porous to allow the passage of appreciable quantities of water through it.

The elevations of water table should be determined at the time borings or test pits are put down or as soon thereafter as a condition of equilibrium has been established. In very porous materials, water will rise almost immediately in an auger hole, or even in a test pit of considerable size, to the level of the water table. In a very tight soil several hours may be required. No general rule can be laid down relative to the time necessary for equilibrium to be established. It depends upon the size of test pit or boring and character of soil. It is readily determined for any particular

case by watching the rise or by taking readings at frequent intervals of time. The rate at which water rises in an auger hole or test pit gives at once an indication of the porosity of the soils adjacent to it. This is especially useful in determining the presence of porous strata which carry or hold water under pressure. When such a stratum is cut water will rise at once from it to a height that will balance the pressure. The elevation to which it rises may ordinarily be considered the ultimate elevation of water table since it is only a question of time, if conditions remain unchanged, until water will be forced upward through the soils to this height.

Hydrographic Surveys.—Data relative to source and amount of water supply are necessary to determine the quantity that must be removed and to furnish a basis for the capacity of drains. Hydrographic data are especially important in dealing with extensive areas where the quantity of water to be removed is large and where efficiency and economy of design require as accurate information as it is possible to obtain.

The character of data necessary to determine a drainage supply varies greatly depending upon whether surface or subsurface waters are involved. In dealing with surface waters much depends upon whether they come at certain flood stages or whether the supply is relatively constant throughout all or a greater part of the year. Information relative to maximum or flood discharges is particularly necessary to determine the capacity of drains required. For a surface supply fed directly by rainfall the tributary area, rate of precipitation, steepness of slopes and character of surface must be considered. The outline or shape of an area determines, in a large measure, the time required for its waters to collect at points where they may be picked up by drains, and consequently influences the maximum discharge. With data concerning rainfall, tributary area and a knowledge of surface and soil conditions it is possible, by using coefficients of runoff, to form an estimate of the supply of water that may be expected under ordinary conditions. It must be understood, however, that all theoretical determinations of this kind, may be subject to wide variations from actual amounts. The most reliable results relative to runoff from a given area are those based upon direct measurements of discharge. These when taken over a series of years give fairly reliable data from which to determine average discharges. It may happen though

that the total or flood flow for any year will greatly exceed any shown by previous records.

Data which may be collected relative to ground water supply are confined principally to sources of such supply, that is, where surface waters are lost into the subsoils. This may include also, seepage, from natural streams where the same occur. In making investigations of this sort it is essential, in so far as possible, to determine the amount of such losses and the areas over which they occur. The character of materials through which seepage waters pass and the steepness of the slopes down which they move are also important. It is sometimes possible, by means of these data and by the use of percolation coefficients, to estimate within rough limits the amount of water which may enter an area from a given source.

Methods of Showing Results.—In order that data may be used to advantage it is essential that it be reduced to a systematic and concise form. It is not sufficient to know that at individual points, certain soil conditions and elevations of ground water do exist. The relationship between results as found at various points must be studied in order to obtain a comprehensive idea of conditions over an area of any considerable size. To do this it is necessary that data be reduced to a form from which the various relationships can be readily seen. Where surface topography alone needs to be considered, as already stated, it can be shown best by means of contours. Where soil and ground water are to be considered some form should be adapted which will show them in clear manner.

Ground water contours may be used to indicate the elevation and configuration of water table, the same as is done for ground surface. To prepare a map of this kind is more difficult and requires a greater number of observations than one showing surface contours for the reason that slopes of water table can not be seen as is the case in dealing with a ground surface. The interpretation of ground water contours is difficult for the reason that they must be compared with surface elevations in order to give meaning to them.

What is ordinarily wanted for a consideration of ground water is its depth below the surface. This may be shown upon a map by means of lines of equal depths. The degree of accuracy with which these can be located depends upon the number of observations taken. Where the slopes of water table vary greatly,

relative to those of the surface, a large number of observations is necessary to draw lines of equal depths with any degree of accuracy. A map showing lines of equal depth of ground water can be accentuated by marking the areas between them with different colors or other distinctive designations. Maps when so prepared serve as a means for showing ground water conditions in a clear and forceful manner. They indicate where ground water is dangerously near to the surface and where protection by drainage is necessary.

For determining the proper location of drains, intended to remove ground waters, it is necessary that data be in such form that the character of subsoils and direction of movement and slopes of ground water can also be seen. The most convenient method, so far discovered, for showing all these is by means of cross sectional profiles, Fig. 9. These should show the elevations of surface, the character of underlying strata and elevations of water table along the lines upon which they are taken.

Direction and Frequency of Sections.—The direction of cross sectional profiles and also the number required on a given area are questions which can be answered only after careful study of local conditions. The direction of sections, generally, should be at or nearly at right angles to the line of surface drainage, or slope. Sections so taken, when their relations to each other are considered, show both the slope that is available and the character of materials that will be cut by drains in any desired locations. They show directly lateral slopes of water table and also the tendency of ground water to move in any particular direction. The latter, as will be seen later, is highly important in determining the location of drains. For convenience in platting and in the study of sections it is desirable that they be made along parallel lines. It is impossible, however, to do this on irregular sloping areas and still keep them at right angles to the direction of natural drainage. The two conditions, consequently, cannot be complied with entirely. It is frequently convenient, especially in cultivated areas to locate sections along established property or subdivision lines. Such locations have an advantage in that their positions are known and excavations on them can be more easily protected than in open fields. Where sections are taken across winding valleys it is necessary to vary their direction in order to keep at right angles to the axis of the valley.

The accuracy with which the surface, subsoil and ground water

can be shown depends upon the frequency of sections taken and also upon the frequency of borings or test pits in each section. It follows that the number necessary on a given area will depend upon both surface and subsoil conditions. The amount of detailed information must also be given consideration. On flat areas, with a subsoil uniform in character, sections at from one half mile to one mile apart may be sufficient. On very rough areas with varying subsoils sections at intervals of 300 feet or less may be required. The determining of locations and frequency of sections corresponds, in a sense, to determining the details of survey and contour interval necessary to show surface topography. It must be remembered, though, that the former involves, in addition to surface profiles, subsurface and ground water conditions and is consequently more complex than the latter.

Two essentials to be determined from subsurface investigations are character of subsoils and elevations and slope of water table. Ordinarily the latter is dependent upon the former due to the different rates at which water will move through the various materials.

In practice it is generally sufficient to make sections at one-half mile intervals where surface slopes and subsoils are uniform; at one-fourth mile intervals, for slightly varying slopes and subsoils, and at from one-sixteenth to one-eighth mile intervals for rough areas or where subsoils vary rapidly. The greatest amount of detail generally is required at or near the bottom of slopes. Here it is frequently necessary to take intermediate sections in order to determine all the information that is needed.

The principal features involved in outlining and making surveys of cross-sectional profiles, are embodied in the following instructions, which have been found useful in outlining field work.

Instructions for Surveying Cross Sectional Profiles.—1. The direction of sections shall be across the line of natural drainage, or greatest slope, and where possible they shall be parallel to each other.

2. Parallel sections when located along north and south or east and west lines shall be referred to rectangular coördinates so that any position on them may be defined as north or south and east or west of these coördinates.

3. Where available, a section corner shall be used as origin of coördinates in order that distances therefrom except fractions of miles, may be determined by means of section lines.

4. In surveying for surface profiles, elevations shall be taken at sufficiently close intervals to permit of a relatively accurate profile of the surface being platted. The distance between readings may vary from 50 feet for rough areas to as much as 500 feet for very smooth slopes. All depressions or natural water ways should be shown.

5. Borings or test pits should be put down at sufficiently close intervals to show the character of subsoils and elevations of water table. It is particularly necessary to find changes in the slope of water table, and variations in the character of subsoils. A consideration of these factors will determine the number of borings or test pits that are necessary.

6. Boring or test pits shall be carried deep enough to show the elevation of ground water, the location of pervious subsoil strata through which it travels and the character of material to the probable depths that drains may be required.

Preparation of Sections.—Sections to be of greatest value should be platted in such manner as to show their relative positions and enable the relation of one to the other to be clearly seen. Experience has shown that this is best accomplished by placing them on a sheet in the same relative positions as on the ground. This is readily accomplished with parallel sections referred to the same system of coördinates. Where the direction of sections must be varied as is the case in winding valleys their variations in direction must be indicated. A somewhat arbitrary rule adopted by the writer is to place sections on a sheet in such manner that in looking over them from bottom to top one is looking up stream. That is, the section taken across the lowest part of the area is placed as the bottom of the sheet and each succeeding one up the slope in its relative position above. Laterally their positions are the same as on the ground so that the one coördinate to which they are referred is shown as a vertical straight line on the drawing. A series of parallel sections when so platted resemble a relief map if we consider each of them as being rotated on its base to a vertical position.

The scale upon which sections should be platted may vary somewhat to suit local conditions.

The elevation of water table and character of subsoils should be shown on sections at points where borings or test pits have been put down. The most convenient form for showing the latter is by means of a log such as indicated in Fig. 7. Profiles of water table and the various subsoil strata should be shown

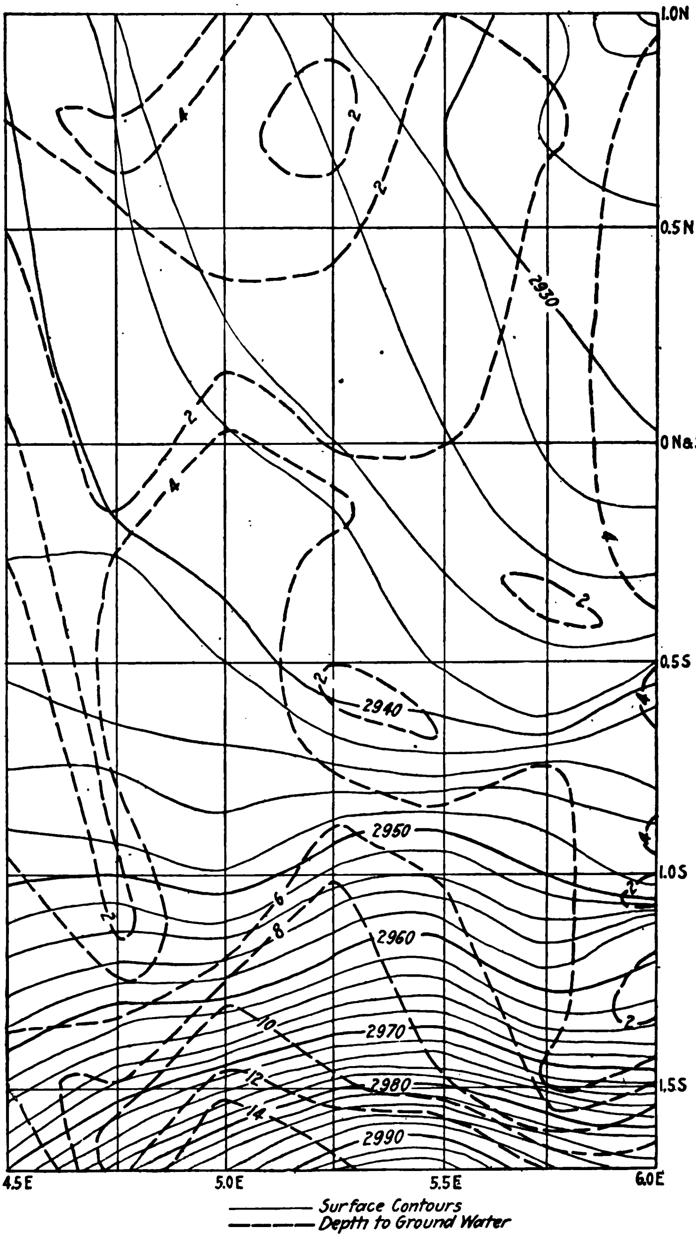

FIG. 8.—Map showing surface elevations and depths of ground water.

1.0

0.5

0.1

by connecting points at observation wells. Such profiles are very useful for indicating the position of ground water and the surface of sand, gravel and shale beds. Their accuracy, as to detail, necessarily depends upon the frequency of borings or test pits and the uniformity of slopes of water table and subsurface strata. It must be borne in mind, always, that definite knowledge relative to underground conditions is confined to points where observations have been made and that between those points variations from a straight line, elevations or depressions, may exist either in water table or in the surfaces of underlying materials. The accuracy of such profiles, on this account, must be considered before basing important conclusions upon them.

Use of Sections in Locating Drains.—In locating drains from sections, the following principal points should be considered: (1) direction of movement of ground water; (2) how drainage must be accomplished, that is, by intercepting underground flow or by the general lowering of an underground reservoir; (3) character of material in which drains are located; (4) natural drainage and the areas protected by it.

The direction of movement of ground water is shown by the slope of water table. This, for the direction along which sections are taken can be gotten directly from them. For other directions it can be gotten by taking the amount of fall between two points on adjacent sections and dividing this by the distance between them. In this manner it is possible to determine the direction of greatest slope of water table or that along which there is the greatest tendency for water movement to take place. Steep slopes of water table may indicate that the movement of ground water is retarded by the presence of dykes or ridges of clay, or other finely divided materials, or that the movement is downward over an inclined stratum of hardpan or rock. In the latter case the slope of water table, generally, will correspond closely to that of the impervious stratum.

The location of drains on steep water table slopes should be such that they will intercept and carry out ground waters before they reach areas where damage may be caused by them. Where ground water is moving down slopes and over an impervious substratum it is generally possible to intercept it near where it first appears on the slope or on the flat area above it. When seepage occurs at or below the foot of slopes due to ground water

moving through pervious substrata from the higher area it can generally be intercepted at or near the foot of the slope. In this position drains, generally, are effective for long distances below them but as a rule do not cause a lowering of the water table for but a short distance on the upper side of them. This is especially the case with tight soils or where the volume of water is large. In either case static head is required to produce a lateral motion of water to the drain and there results a holding up of water table at short distances from it. Instances have been found where deep drains did not lower the water table for more than 100 feet from them on the upper side, while on the lower side their effect was shown at distances of from 1000 to 2000 feet.

Sections taken parallel to slopes provide data for determining where ground water may be tapped and carried away from the foot of slopes. The method of locating a drain of this sort is to determine at what point it should cross each of the sections in order to intercept water coming from above. These points should then be located on the ground and joined by the most feasible line. The elevations and distances apart of points in the various sections provide data by means of which a rough profile of the line can be plotted and its grade determined before being finally located on the ground.

When seepage occurs over large relatively flat or uniformly sloping areas and is not the result of water coming directly from adjacent higher lands drainage ordinarily must be accomplished by affecting a general lowering of the water table over them. In such cases the subsoils, as a rule, are sufficiently porous to permit of a relatively free percolation through them, but the quantity of water which they contain is sufficient to raise the water table near to the surface. The direction of water movement generally is down the line of greatest surface slope. The water in the soils may be and generally is the result of rainfall or excess irrigation on the lands themselves. In some instances it may come through deep pervious subsoils from a distant source. Drainage for these conditions is manifestly impossible by intercepting waters before they reach the affected areas, but must be accomplished by a process of skimming of the top portion of the ground waters. Sections taken at right angles to the line of greatest slope give the necessary data for locating drains of this character. In using them the points of highest ground water and where each section should be cut by drains to lower the water table should be deter-

mined. Surface depressions which may serve as drain locations and save excavation and also the water carrying properties of subsoils must also be considered. When the points at which the various sections should be crossed have been determined locations between these may be made as heretofore described. The direction of drains, for conditions described above, generally is along the line of greatest surface slope. This gives the greatest amount of fall available and also prevents seepage from drains which may do damage.

Natural drainage conditions frequently serve to prevent the rise in water table and obviate the necessity of artificial drainage over portions of an area. This often occurs when porous subsoils afford an outlet to lower lands or to natural drainage channels; this condition is shown on sections by a fall in water table. In locating drains on areas that are partly protected by natural drainage, the effect of the latter should be considered and drains located so as to supplement it as far as is possible. To do this drains, in so far as practicable, should be so located that they will not cross areas where natural drainage takes place. If this precaution is not taken the natural drainage capacity may be fully taxed by the drainage waters discharged onto it, and fail to serve its original function of keeping down the water table.

CHAPTER VII

LOCATION AND DEPTH OF DRAINS

Factors to be Considered.—In determining plans for drainage works, especially locations and depths to be adopted, physical features and drainage requirements must be considered. The physical factors which enter most prominently are topography, character of soils and source or sources of water supply. Often topography is of prime importance since it frequently determines the general plan that must be used and fixes within narrow limits the possible locations. The first work of locating drains should be to determine where they may be placed so as to provide necessary slopes and, at the same time, avoid excessive costs for excavation. It is important that the general plan of a system be sufficiently comprehensive that it may be made to serve, as outlets at least, for the entire tributary area to be drained. Main drains intended to serve as outlets for several tributary branches, or which, for other reasons, may be required to carry large quantities of water, generally, should be located along lines of greatest slopes in order to avoid losses from them, either by underground seepage or by overflow of flood waters. The principle of locating drains along lines of greatest slopes does not apply to small drains intended principally for intercepting water below a source of supply. Here, as will be seen later, it is frequently necessary to make locations nearly at right angles to natural slopes.

Another important requirement, especially with open drains intended to carry large quantities of water, is that they be located, in so far as possible, along lines of uniform slopes. Drains constructed with varying slopes tend to erode where slopes are steep, and to deposit the eroded materials where they are flat. This causes a raising of the grade and a lessening of the effectiveness of the drain where such filling takes place. This is generally on flat areas where drainage is most needed. Drains with varying slopes require a greater amount of maintenance work to keep them in a condition of maximum efficiency than those of

uniform slopes other conditions being similar. In most instances, especially over rough areas, it is impossible to locate drains so that they can be given truly uniform slopes without, in places, resorting to excess depths of excavation. By a careful study of the topography either by means of contour maps or by cross-sectional profiles it is possible, however, to reduce variations to a minimum. The number of drains necessary for a given area, in some instances, is determined largely if not wholly by its topography. This is the case where small areas, as for example a series of narrow valleys, are separated by ridges too high to permit of drains being constructed through them. The area that a drain will serve under such conditions is limited to that of the depression or valley through which it passes. On flat or uniformly sloping areas, factors other than topography, are generally of first importance in determining the number and location of drains.

The depths of drains, and on some areas the number required, depend largely upon soil and subsoil conditions. The depths below the surface at which ground waters can be tapped and carried out of the soils depends upon the depths of porous or water-bearing strata through which the waters are percolating. The depths at which ground waters should be maintained depends in some degree upon the texture of soils. The distance that drains will be effective depends largely upon the rate at which water will move through the soils or subsoils adjacent to them. A knowledge of the source of supply is fundamentally necessary to locate drains so that it may be reached.

Purpose a Drain is Intended to Serve.—In determining the location and character of a drain, it is desirable that definite conclusions be reached or assumptions made, of what it is intended to accomplish. It is by this method only that a comprehensive plan for the drainage of a given area can be worked out. By locating each drain with a view to its accomplishing certain definite results, it is possible to provide protection to the entire area involved and at the same time avoid, in so far as is possible, duplicate and unnecessary construction. It is not to be inferred from the above that the distance a drain will be effective, or the area that will be reclaimed or protected by it can be accurately determined in advance of construction. Neither is it to be understood that the planning of works for the complete drainage of a given area in advance of construction is always

feasible or possible. It is frequently necessary to observe the results of drains already constructed before sound conclusions can be reached as to what will ultimately be required. It is possible though, in most cases, to determine within reasonable limits what the effect of a drain will be and to provide for additional ones when needed, without duplication. It is frequently necessary in making drainage plans, especially on large areas, to provide for future extensions or additions. Where this is the case the first works should be so planned that they will form an integral part of the enlarged or completed system.

In order to locate drains for specific purposes careful consideration must be given to the character of soils and the manner in which water may be best reached and carried out of them. As a specific example consider the case of a flat or gently sloping area of uniform but relatively impervious soil to a depth of several feet. Such conditions would permit a free but very slow percolation of ground water to all parts of the area. Assume also that the water table is high but at nearly uniform depth below the surface. Conditions like these are common both in the humid areas and on irrigated lands. From the character of soils and the fact that the depth to water table is relatively constant it is readily seen that the supply is of such character that water is distributed more or less uniformly over the area. If this were not the case the resistance of the soils would cause the water table to stand higher where water enters the area than on other parts of it. There are two ways by which water may thus reach the soil; one is by uniform distribution over the surface, the result of precipitation or irrigation. The other is by an underground supply confined in deep pervious strata such for example as gravel or coarse water bearing sand. In the later case the water moves freely through the pervious substrata and by the pressure under which it is confined is gradually forced upward into the tight soils and the water table raised.

Drainage in the two cases referred to differs widely, and generally must be accomplished by radically different methods. Where the excess water is the result of a uniformly distributed surface supply, as in the first case, drainage consists of drawing water out of the soils sufficient to lower the free ground water to the required depth. Drains consequently must be located and constructed in such manner as to best accomplish this result. The number required or their frequency depends upon the

freedom with which water will percolate through the soils to them and also upon the amount of water that must be removed. The depths of drains is also a factor in determining the number required, since a deep drain generally will be effective at a greater distance than a shallow one. Conclusions relative to the number of drains required can be reached only from a study of the water supply and results of experience on percolation in different soils.

In the second case drainage is essentially the tapping of an underground supply so as to relieve the pressure which it exerts upon the soils above. This may be accomplished by constructing drains directly into the water bearing sands or gravel, of which the underground reservoir is composed. The manner in which these can be tapped to advantage requires special study of each individual case. In some instances it can be done by drains excavated directly into the water bearing materials, while in others it must be accomplished by means of relief wells carried downward from the bottom of deep drains. The principle which is especially desired to illustrate here is the necessity for determining how drainage may be accomplished and the planning of works for this particular purpose.

Intercepting Drains.—Reference has already been made to the method of protecting lands from excess water by cutting off and diverting the supply away from them. It remains to make a somewhat more detailed study of the conditions where such a plan is applicable.

Intercepting drains, generally, may be used where water is found to be travelling down slopes but they are more frequently applicable where the slopes change from steep ones above to flatter ones below. The ideal conditions for an intercepting drain are those where the drain can be excavated into an impervious material below the porous strata through which water is travelling. With these conditions an intercepting drain may be made effective for removing all of the supply, both surface and underground, which would normally cross the line of its location. Cases like the one described above are occasionally found in areas of heavy impervious clay overlaid by more or less pervious top soils. Generally, though, intercepting drains must be constructed in porous materials. Here their effectiveness depends largely upon the materials under the bottom of the drain, and the freedom with which water passing through them may reach the surface. The controlling factors in the latter are the steepness

of the slopes and the character of materials on the lower side of the drain. A drain constructed along the upper side of a flat area, even though in porous materials, may lower the ground water sufficiently to keep it at a safe depth below the surface for

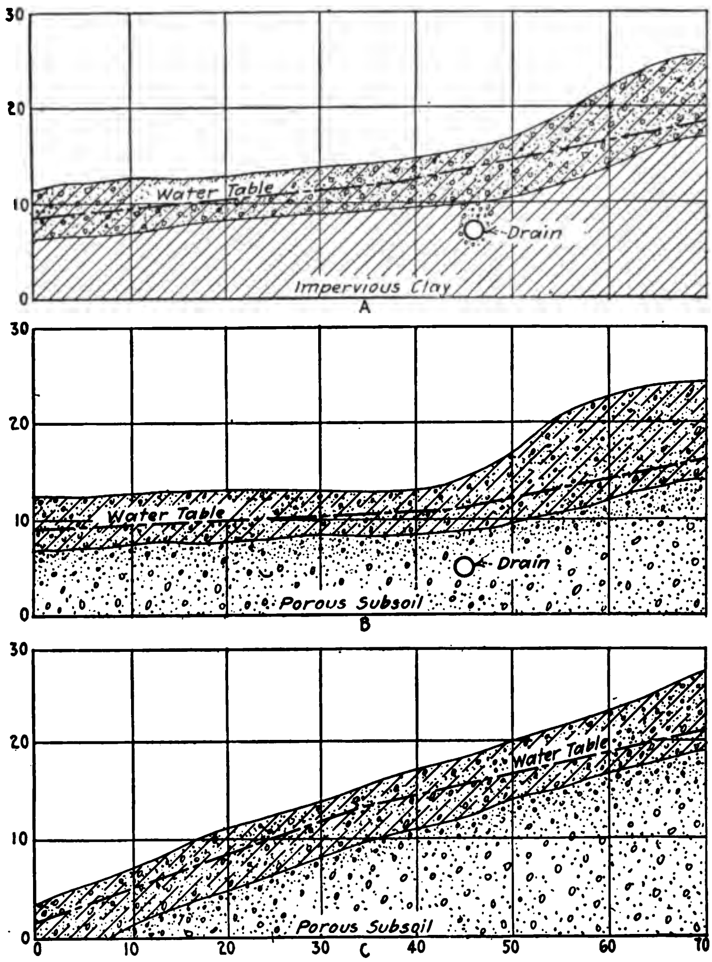

FIG. 10.—Sections illustrating action of drains on slopes.

a long distance on the lower side of the drain. If, however, the slopes on the lower side are steep the water which passes under the drain may come to the surface a short distance from it.

The application of intercepting drains to different conditions is shown in Fig. 10. Sections A, B, and C are taken along the

line of slope, which is also the direction of greatest water movement. They show the character of soils and subsoils and the elevations of ground water. Section A presents ideal conditions for intercepting water. A drain constructed at the location and to the depth shown would intercept any flow coming down the slope, since it must all travel over the impervious clay substratum.

Section B shows a deep subsoil of porous sand and gravel, through which water will travel freely. A drain built across this section where indicated would not intercept all the water travelling down the slope on account of part of it passing through the porous material below the bottom of the drain. It would, however, prevent water passing at a sufficiently high elevation to do damage to lands on the lower side of the drain.

Section C shows conditions where water would be intercepted by a drain across it at practically any point, but on account of the steep slopes, and the freedom with which water would travel through the porous materials underneath the bottom of the drain, it is not certain that any considerable area would be protected on the lower side of it. Where conditions such as shown by C prevail, a surer method is to construct drains along the line of greatest slope.

Other examples of intercepting drains could be given; these, however, are sufficient to show their general application. An impervious substratum is necessary to completely intercept water travelling down a slope; where porous strata exist underneath the bottom of drains, water may percolate freely through them. This on steep slopes may soon find its way to the surface and become a source of damage to lands.

Relief Drains.—This term is commonly applied to drains intended to effect a general drawing off of water from a given area. They are designed to draw water out of the soils on both sides of them and, in this manner, to effect a general lowering of them and, in this manner, to effect a general lowering of water table. Unlike intercepting drains they are not intended, primarily, to cut off or intercept water travelling in a given direction. They, however, do perform this function to some extent since ground water always has some movement and drawing it out of the soils on one area has the effect of lessening the amount that will reach adjacent ones.

Relief drains, generally, are adapted to conditions where excess

waters to be removed are distributed more or less uniformly over the area to be drained. Drainage under these conditions consists in carrying out ground water at sufficiently close intervals and to the necessary depths to effect a general lowering of water table over the entire area. Conditions of this kind are commonly found on flat areas where the precipitation or water applied is greater than the total that can be used by vegetation and disposed of by natural drainage. The excess waters which pass into the subsoils are held, in part, by impervious strata below and a gradual filling up of the soil spaces results.

Water is collected by relief drains through lateral percolation toward them. This lateral flow is sometimes complex in character and may take place through the soil as a mass or through strata of porous materials only. Where the soil is homogeneous in character, the lateral flow through it is necessarily confined to that portion which is higher than the water in the drain. Where it is stratified, water may follow the porous strata through very irregular paths. It may sink below the level of the drain and again be brought up to it, due to the pressure under which it is travelling. In some tight soils the lateral movement of water through them is so slow that drains are required at frequent intervals, in order to draw the excess water out of them. In others it may be effected by tapping porous sand or gravel strata. In the latter case the excess soil water percolates slowly downward to these strata and is carried by them to the drains.

Extent of Effect of Drains.—The distance, on either side, that a drain will be effective in reducing the water content of soils depends upon many and variable factors. Among them may be mentioned, depth of drains, source and amount of water to be removed, and character of soils through which percolation takes place.

In the discussion of intercepting drains, it has been shown that under certain conditions, the water reaching a given area from an exterior source may be all intercepted and carried out of the soils. In other instances, that which enters an area may be, in part, intercepted and drawn out. The distance on the lower side of the drain to which it will be effective, is largely a question of slopes and can be determined within reasonable limits from cross-sections. Where water is intercepted, the water table on the lower side of the drain will be lowered to or below the elevation of water in the drain. From the steepness of slopes it may

be readily determined how far the minimum effect, that is the keeping of ground-water level with that in the drain, will afford protection to the lands.

The lowering of water table by means of relief drains takes place on both sides of the drains and is greatest ordinarily immediately adjacent to them. This drawing down of ground water along the line of drains affords an outlet for lands farther distant, and the effect widens until a condition of equilibrium between porosity of soils, quantity of flow, and slopes is estab-

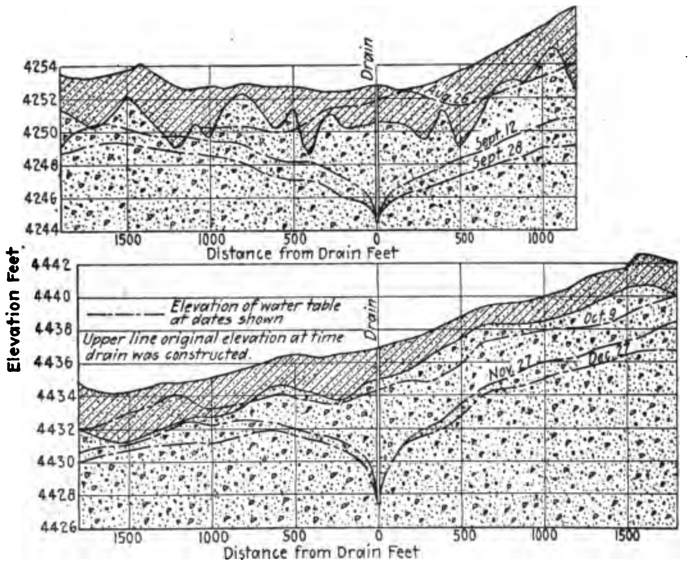

FIG. 11.—Sections showing effects of drains in coarse gravel.

lished. The first of these depends upon the character and texture of soils, the second upon the amount of water which must be removed. On account of these variable and to a large degree, indeterminate factors it is impossible to predict with any degree of certainty the character of the vertical curve of water table laterally from a drain. Formulas that have been developed for rates of percolation are applicable only when the soil texture is relatively homogeneous and when the amount of water that must be removed from a given area is known. Both of these conditions are seldom found in actual experience. Theoretical determinations of the distance to which a drain will be effective frequently differ widely from actual results. These discrepan-

cies may be due to variations in porosity of soils that could not readily be determined in advance of construction, or to the development of more or less water per unit of area than had been estimated.

For the purpose of considering effects of drains in them, soils may be classified as tight, semi-porous and porous. The first includes clays and very fine homogeneous sedimentary deposits; the second, sandy or gravelly loams and those containing porous strata; the third, sands, gravels, and other equally previous materials. In this it is to be understood that, generally, there is no sharp line of demarcation between these classes.

Observations on different classes of soils show that some are so tight as to practically prevent the passage of water through them. Drains in such soils are not effective for removing ground water, and in many instances produce no change in the elevation of the water table immediately adjacent to them. The maximum distance to which drains may be expected to be effective in reasonably tight soils, generally, does not exceed 200 feet. In semi-porous soils, their effect may extend to 1000 feet and in porous soils to one mile or even more.

Maximum Effects of Drains.—In the preceding section reference has been made to the maximum distances to which it may be expected drains will have an effect in drawing out ground waters. It should not be concluded from this that drains will always, or even generally, act with sufficient effect at these distances to give full protection to soils. Water may move out of the soil, due to the effect of drains but not at a rate sufficient to hold the water table down to the required depth.

The most important consideration in locating drains is that they be so placed that maximum effects will be obtained. This is necessary for successful and economic results; to accomplish this drains must be located where the greatest amount of water will be developed, and where its removal will have the maximum effect in protecting lands. They must be placed in the most porous materials available in order to give free inlet of water to them. This generally requires a careful search for strata of sand, gravel or other porous materials. Where water exists under pressure below a tight soil, it is necessary that the strata containing it be tapped and the water drawn out. This will relieve the pressure and prevent water being forced upward into the soil.

The slow rate at which water moves through what has been termed tight soils, requires that they be protected, as far as it is possible, by preventing excess water entering them. This may be accomplished first by draining away surface waters and second by tapping porous materials adjacent to them. Water-logging in tight soils developes slowly on account the resistance they offer to water entering them. This fact makes it possible, in many instances, to divert and carry away excess waters before damage is done by them.

Deep and Shallow Drains.—Deep or subsurface drains, as they are sometimes called, are those excavated deep enough to have effect in drawing ground waters laterally to them. Shallow or surface drains are designed primarily to carry water away from the surface. It is to be understood that there is no sharply marked limit between these two classes since the functions performed by each are, to some extent, common in character. There is also no fixed limit of depth between deep and shallow drains; since this may vary with different character and conditions of soil. Generally, however, drains less than five or six feet deep may be classed as shallow, while those of greater depths may be classed as deep drains.

Deep drains which are intended primarily, to receive water from the soils adjacent to them should be located where ground water may be most readily tapped, both as regards elevation of water table and character of soils. Shallow drains intended to collect water from the surface, should be located where surface waters can be conveyed to them most conveniently. From this it is readily seen that locations in the first case should be determined from underground, and in the latter case, from surface conditions. It follows also that a system of deep and shallow drains, even on the same area, might vary greatly as to locations.

What May be Accomplished by Shallow Drains.—As all drainage construction has for its ultimate purpose the improvement of soil conditions, one of the fundamental questions to be answered in each case, is, what may be accomplished by drains of a particular type? It has been stated that the principal function of shallow drains is to remove surface water. It may be said that in most cases they also exert a limited influence on ground waters adjacent to them. It is necessary to consider the particular conditions under which shallow drains are sufficient

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to provide the necessary protection to soils. In general, shallow drains are adapted more especially to conditions found in the humid areas, than to those on irrigated lands. There are some instances, however, where they are applicable in the latter case.

The conditions under which shallow drains may be advantageously employed may be summarized as follows:

(*a*) Where water travels down slopes onto lower areas, it may be intercepted and carried away by shallow drains; provided such flow is on or near the surface. This may be the case where soils are relatively tight or where they are underlaid at shallow depths by an impervious stratum which prevents the downward percolation of water through them.

(*b*) Where shallow porous or semi-porous soils, with relatively flat slopes, are underlaid by a stratum of clay or other impervious material, excess waters may be drawn out of them by means of drains cut deep enough to form a water-way in the impervious material. In this case water moves to the drains partly through the pervious top soils and partly over the top of the underlying tight stratum; that is along the plane of contact between the two different materials. Drains of this sort are fed by soil waters, which move below the surface and although shallow, are not strictly surface drains. Conditions like the above are common in humid areas, and in some instances also on irrigated lands. It is to be understood that for shallow drains to be effective in this case the excess water in soils must come directly from the surface and not from ground waters, being forced upward. The surface supply also must be distributed more or less uniformly. These conditions may result from heavy precipitation or from the application, through irrigation, of more water than is required for plant growth. Drains of this type are generally required at comparatively frequent intervals.

(*c*) Where flat or gently sloping areas of tight soils are seeped or water-logged from a uniformly distributed surface supply, such for example as excess rainfall or even from irrigation; the excess water may be collected and carried away by shallow surface drains, and thus prevented from entering the soils. The drainage water in this case is taken directly from the surface, and topography should be considered principally in making locations. That is, drains should be placed where they will collect the largest amount of surface water. This method of drainage, although applicable in some cases to irrigated lands, is seldom necessary

or advisable for this purpose. A better remedy is to regulate the amount of water applied so as to avoid surface waste.

In the use of shallow drains, consideration should always be given to the fact that the only effect they can have on deep soil strata is through the carrying away of excess water before it reaches them.

Conditions Which Make Deep Drains Necessary.—It has been shown that in some instances protection may be provided for soils by means of shallow drains. There are, however, some conditions of soils that require deep drains for their protection. These are more commonly found on irrigated lands than in the humid areas, on account of fundamental soil differences in the two cases. The necessity for deep drains may be the result of character of soil formation, chemical constituents of soils—that is the presence of alkali in them—amount and seasonal distribution of water supply, and character of crops to be grown. Ordinarily the first two are the predominant ones but the others are of sufficient importance to require consideration in many cases. Irregular topography or flat slopes may also require deep cuts, these, however, are not strictly drainage requirements, but refer more especially to outlets.

The conditions under which deep drains are required to give protection to soils may be enumerated as follows:

(*a*) Where a deep soil of a tight or semi-pervious character is underlaid by porous materials, deep drains are required to tap the porous substratum and provide an outlet for water from it. It matters not, in this case, whether the excess water comes from a uniformly distributed surface supply or from an exterior source. If an excess supply is distributed to the surface it will gradually find its way downward to the pervious strata which will act as a sort of reservoir for retaining it. Shallow drains, under these conditions, have but little effect for the reason that the lateral movement of water through the top soil is slow and the amount which reaches them is small compared with that which percolates downward to the porous substrata. The water in the subsoils ordinarily is under more or less pressure, the head on it being equal approximately to the height of free water above it. If a small amount of water be drawn out of the top soils by means of a shallow drain the upward pressure may be sufficient to maintain a high water table immediately adjacent to it. This condition is illustrated in Fig. 12 which shows a

section of tight soil underlaid at depths of from six to eight feet by porous gravel which contains water under pressure sufficient to raise it to the elevation *W*. Free water will consequently stand at this elevation. If water be drawn out at *D* the effect will be to lower the water table at and immediately adjacent to that point. At a short distance from it, as, for example, at *B* there will be no change in the elevation of the water table since the upward percolation from the reservoir below is equal to or greater than the lateral motion to the drain. The above described conditions will prevail under soil conditions similar to those shown and where the supply of water which reaches the

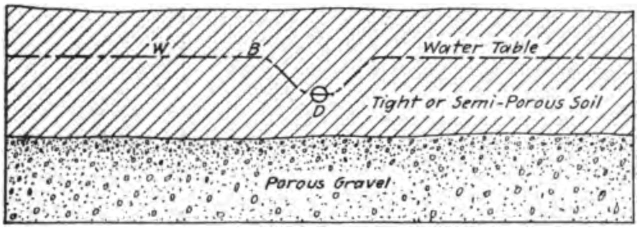

FIG. 12.—Section illustrating action of drain in tight soil.

porous gravel is greater than the capacity of natural drainage from it. By tapping the porous strata and drawing the water out of it the top soils are given a free outlet downward. It may be questioned why water will move more freely downward than it will laterally through the tight or semi-pervious top soils. A consideration of the relative distance, water must travel downward to reach porous material or laterally to reach drains, at reasonable distances apart, will answer this question.

(*b*) In deep homogeneous soils through which water moves with relative freedom but where the supply is in excess of plant requirements and natural drainage capacity, deep drains are necessary to provide for the upward slopes of water table on either side and at the same time hold it at a safe depth between drains. This is the case regardless of whether the supply of excess water is uniformly distributed over the surface or whether it is distributed partly by lateral motion through the soils.

(*c*) In some cases the elevation of water table varies greatly during different seasons, and at times approaches dangerously near to the surface. This condition is due generally to a varying supply sufficient at times to entirely fill the soils. In such

cases deep drains serve to draw down the ground water and during the period of low supply to provide storage in the subsoils which will in part absorb flood flows and assist in keeping the water table at a safe depth.

(*d*) Deep drains are necessary in reclaiming and protecting lands from injury due to alkali. Here it is necessary to keep the water table at a sufficient depth to prevent harmful soluble salts being brought up and deposited on or near the surface through capillary action and evaporation. It is necessary, also, especially where salts have to be washed out of the soils, to provide for a downward motion of the excess water through them.

(*e*) Deep drains are required where it is necessary to protect soils for deep rooted crops and trees.

Drainage by Relief Wells.[1]—Reference has been made, in

[1] Relief wells as an aid to drainage, so far as known, were first used by Joseph Elkington of Warwickshire, England, about 1764. John Jonstone in a work published in 1797 and entitled "An Account of the Most Approved Mode of Draining Land as Practised by Mr. Joseph Elkington" stated that the discovery of this method was accidental. Mr. Elkington had constructed a drain across his lands, the results of which, were unsatisfactory. Consideration was being given to deepening the drain when upon exploring with an iron bar to determine the character of material that would have to be excavated, free water was encountered in a porous stratum a few feet below the bottom of the drain. This water which was under pressure rose rapidly and caused an appreciable flow in the drain. This led to the conclusion that water was confined below the impervious top soils. By an application of the principle then discovered, the successful drainage of the lands was accomplished by means of wells sunk below the drain. From these experiments this application of relief wells was further developed and used by Mr. Elkington in his work of draining land in various parts of the United Kingdom.

The use of relief wells in the United States has been confined largely to irrigated areas; here on account of the prevalence of porous subsoils, their use in many instances, is especially applicable. They have been used by the author on lands underlaid by sand, gravel, fissured clay, and porous rock, with satisfactory results.

On the Huntley project, Montana, wells were used under drains in soils of heavy clay or adobe underlaid at depths of from twelve to fifteen feet by sand and gravel strata: At Polson, Montana, Flathead Project, they were used under drains on slopes of from two to four feet per hundred. Here the soil which somewhat resembled clay in general apperance is composed of finely divided rock particles and is relatively impervious to water. The underground supply reached the affected area in a gravel stratum at from thirty to fifty feet deep, and under sufficient head to force it to the surface. To relieve this pressure wells were sunk to depths of from twenty to forty feet below the bottom of deep closed drains. The flow from the wells was com-

former paragraphs, to water found in porous subsoils but confined below a top stratum of clay or other impervious materials. In such cases there is an upward pressure equal to the head on the confined ground water less that lost through friction and percolation. This pressure may be and frequently is sufficient to force water to the surface: if the ground water be tapped by means of wells an artesian flow will result. The upward pressure gradually produces a condition of saturation in the tight soils above and the plane of saturation or water table rises until a condition of equilibrium is established. Drainage under these conditions must be accomplished by tapping the source of supply, or in other words, by providing outlets from the porous substrata. When these are at relatively shallow depths they may be tapped directly by drains; when they are below the depths to which it is practical to construct drains, it is possible, in many instances, to afford relief by connecting the porous strata with deep drains by means of wells.

The principle involved in using relief wells is that of reducing the head or pressure of the underground water so that it will not be forced high enough to do damage to top soils. To accomplish this, wells must be sunk well into the water bearing materials so as to give a free inlet to them, and the water which

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paratively small ranging from about three to twenty-five gallons per minute. The wells were effective in relieving the pressure at the elevations upon which they were located but on account of the steep surface slopes, their range of effect was limited.

On the North Platte project in Western Nebraska are large areas underlaid by fissured brule clay; this clay during a portion of the irrigation season carried water under pressure sufficient to force it to the surface and form ponds over considerable areas. The depth to clay over these areas generally ranged from ten to twenty feet and it was impracticable to reach it directly by drains at sufficient depths to relieve the upward pressure. Drains excavated in the top soils to depths of from eight to ten feet had little or no effect; in some instances ground water would stand on the surface immediately adjacent to them. By the use of relief wells sunk into the brule clay it was found possible, in most instances, to tap the underground supply and carry away sufficient of it to lower the water table to a safe depth. In this work a large number of wells had to be put down on account of many of them not coming in contact with fissures and yielding but little flow. Where fissures were struck, large quantities were developed.

On the Carlsbad project in New Mexico, relief wells were employed with good results in porous gypsum rock. The water developed by these wells was found principally at depths of from fifteen to twenty feet below the surface.

FIG. A.—Water standing on surface over tile drain, the result of water under pressure in deep porous strata.

FIG. B.—Same location as above, showing condition after relief well had been sunk in trap box under drain. North Platte Project, Nebraska.

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PLATE VI

FIG. C.—Interior view drainage pumping plant, Yuma Valley, Arizona.

FIG. D.—Exterior view drainage pumping plant, Yuma Valley, Arizona.

This plant is intended to serve for the disposal of drainage water from about 50,000 acres which is without gravity outlet. The water is lifted from 8 to 15 feet depending upon the stage of the river, and discharged through the levee which protects the valley from overflow during flood stages. The *plant* is designed for an ultimate capacity of 175 second feet and consists of three 50 and one 25 second foot units. Two of the units have been installed.

rises in wells must be tapped and carried out at a sufficient depth to protect the soils above. The latter is the depth at which free ground water should be maintained to provide the necessary zone of unsaturated soil for plant roots. The effective depths of drains, fed by relief wells, is that at which the wells discharge into them. This is the limit to which the pressure head on the underground supply can be reduced. At lower elevations there is still an upward pressure tending to produce saturation in

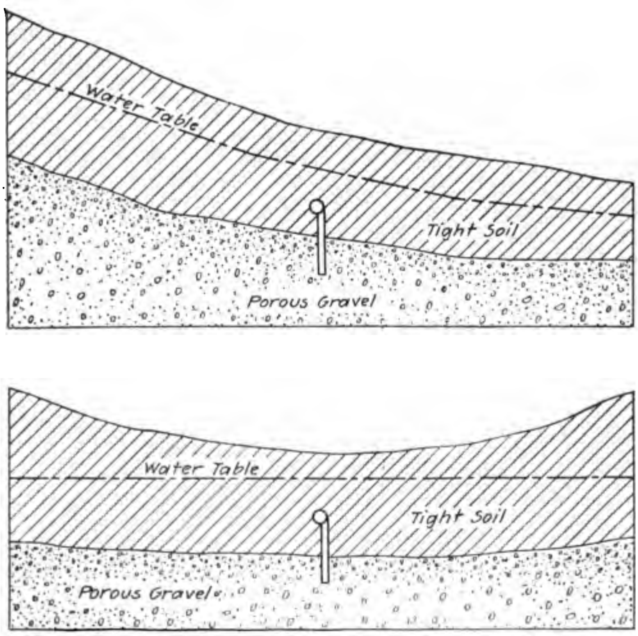


FIG. 13.—Sections illustrating action of relief wells.

the soils. Fig. 13 shows sections where conditions are favorable for relief wells and indicates locations for drains for their use.

The number of wells required, or their frequency, along a drain, depends upon the freedom with which water moves through the deep porous strata. For efficient drainage, there must be a sufficient number to reduce the pressure head in subsoil to the elevation of water surrface in the drain. Experience has shown that they may be needed at intervals of fifty feet or less in some soils, while in others they may be placed from four to five hundred feet apart and give satisfactory results.

Wells should be of sufficient size to carry the water developed without appreciable loss of head; they should be sufficiently large also to offer reasonable assurance against becoming obstructed. Ordinarily sizes of from three to six inches in diameter are sufficient. They should be cased or otherwise protected from being destroyed due to walls caving. The top of casings should be screened to prevent rocks or other obstructions falling into them. Where the discharge is into closed drains, wells may be placed at one side of the drain and a cross connection made between them. Where the flow from the well is small this connection may be made of coarse gravel or broken rock. Where large flows are encountered, an elbow or angle may be used for connecting the well casing to drain pipe.

Drainage by Pumping from Wells.—Pumping from wells some times provides a means for lowering ground water. In some instances it is impracticable or impossible to tap water bearing strata by drains, or even by relief wells under them, so as to produce the necessary effect in taking water out of the soils, and pumping is the only economic and effective method that can be employed.

The condition to which pumping is especially adapted is a deep formation of sufficiently porous material to allow a large quantity of water being collected at a single well. The deep porous formation may extend to the surface or it may consist simply of underlying stratum or strata covered by relatively tight materials. In the latter case water may be held in the porous strata under sufficient pressure to force it slowly upward to the surface.

An essential requirement for efficient drainage by pumping is that the deep water bearing material be thick enough to permit of a considerable flow through it. Drainage is accomplished by pumping out sufficient to produce a general lowering of the ground water. This is practical only when a free flow to wells can be obtained.

The conditions under which pumping from wells furnishes the only economic and effective means for drainage is where the water bearing material is so deep that it cannot be tapped direct and water carried out by gravity. It is possible very often to tap underground strata by relief wells and carry water upward through them to drains. The flow from such wells is generally small, on account of their discharge being relatively near to the

surface, and a large number of wells is necessary to accomplish results. Where water bearing strata are deep, the cost of con-

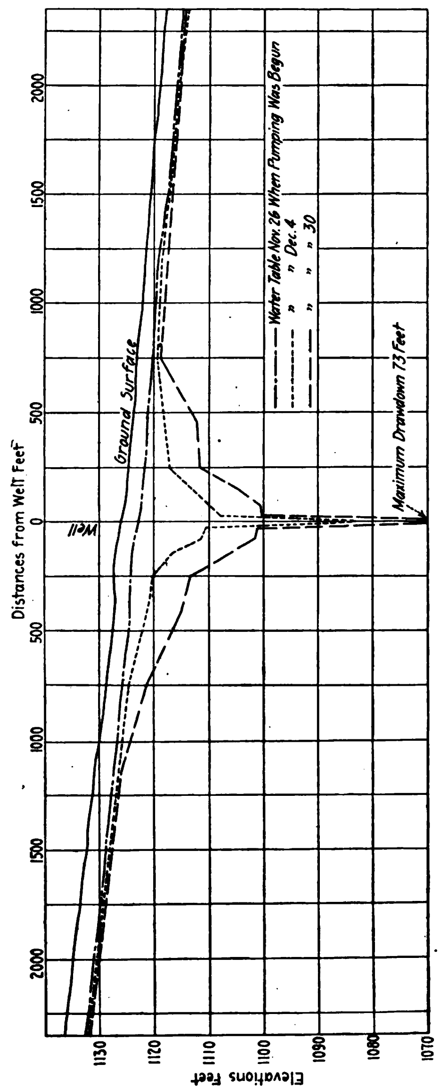
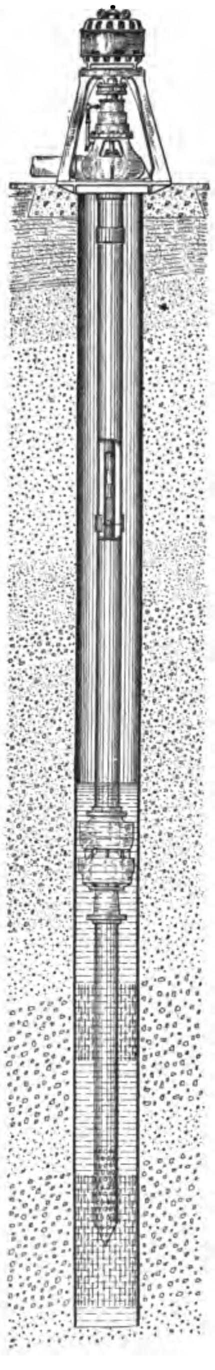


FIG. 14.—Section through well showing draw down of ground water by pumping. Salt River Valley, Arizona.

structing relief wells at sufficiently close intervals to have the required effect may be prohibitive.

Drainage by pumping, where conditions are favorable for it,



permits of ground water being lowered to a greater depth than is practicable by any other method. This is an advantage on account of its adaptability to any special soil or crop requirements. Also where the ground water supply is subject to extreme fluctuations, the water table can be lowered during dry periods and a storage capacity created which will aid in taking care of high water stages. Pumping operations, in some instances, may be suspended during a part of the year by first lowering the ground water sufficient to provide storage for the inflow during that period.

The distance from it that a well will be effective in lowering ground water, or the number of wells required for a given area depends upon the slopes and character of the underground formation. The greater the porosity of the water-bearing materials, the larger the quantity that can be developed by a single well and the greater the effect it will produce. It is not an uncommon experience for a well to have an effect at a distance of one-half mile or more from it. The curves of draw down are frequently irregular and show a greater effect in one direction than another. This may be due to different formations, which accelerate or retard the flow, or to a greater supply coming from one direction than another.

To produce an economic lowering of ground water over a large area a number of wells is necessary. They should be located far enough apart to prevent their having a marked influence upon each

FIG. 15.—Type of well and electrically operated pump commonly used for pumping from deep water-bearing strata.

other and thus reduce the lift on each to a minimum. In locating wells for drainage purposes the same general principles apply as in locating drains. To be effective, they must be sunk into water-bearing materials; they should also be placed where they will effect the greatest possible area. Where water is travelling down slopes, in deep porous strata it is frequently possible to intercept it by wells and protect areas below in much the same manner as by drains.

In pumping for drainage it is necessary also to provide means for disposing of the water after it is brought to the surface. This may be done by carrying it to natural water ways through shallow drains, or it may be used where there is a demand for it. In the arid region the extent of irrigation development depends ultimately upon the amount of water than can be made available. Drainage water is valuable for supplementing an irrigation supply, provided it can be delivered where required for use and its quality is satisfactory.

Gravity drains, generally, discharge below the irrigated area, where it is impractical to deliver the water to irrigation canals. Drainage water is frequently unfit for irrigation, on account of harmful salts which it contains in solution, unless mixed with several times its volume of relatively pure water. Pumping from wells, on the irrigated area, permits of water being delivered into irrigation canals or laterals and mixed with other water in the necessary proportions to render the quality of the mixture satisfactory.

It is sometimes economy to remove excess water from the soils by pumping from wells rather than by means of drains. This is especially the case where the pumped water has a high value for supplementing an irrigation supply.

Pumping for Disposal of Drainage Water.—It is sometimes the case that a main drain cannot be discharged by gravity into a natural waterway, and pumping is necessary at the lower end of the system to dispose of the water. This condition applies to flat or depressed areas, and to valleys traversed by streams, the beds of which are at about the same elevation as the lands adjacent to them. The latter is often the case where streams have been built up by sedimentary deposits. Good examples of conditions unfavorable for gravity outlets are found on the lower reaches of the Colorado and Sacramento Rivers, and many other similar streams. They are common also in swamp and lake regions throughout the country.

It is sometimes advisable to use a combination of gravity and pumping from the same area; that is to dispose of the drainage water from the upper portion through a gravity outlet, and thus reduce the amount of pumping required. This is applicable on areas containing both bench and valley lands or what is sometimes termed highland and lowland drainage. The bench land, a short distance back from the stream may be drained through gravity outlets; on those lands immediately adjacent to the stream pumping is required. It may apply also to portions of the lower lands where the general slope of the valley is relatively steep, and where the area to be drained extends for some distance up and down the stream. The plan in this case is to discharge water from the higher part of the area through a gravity outlet, whose slope is less than that of the valley. Where a combined system of this kind is used the gravity drains should be located so as to intercept the flow of water onto the lower area as much as possible and thus reduce the amount that must be removed from it to a minimum.

The essential requirements for a pumping plant to dispose of drainage waters are capacity and reliability. It must serve the purpose of an outlet for a drainage system, and should be sufficient to care for maximum flows that may be developed. For determining the capacity of a plant, the same methods will apply as for determining the capacity of a drainage outlet.

A plant should be designed and constructed for continuous service. The periodic operation of a drainage system reduces its efficiency and is also detrimental to the works. An objection sometimes urged against pumping for drainage outlets, is that it is possible for pumping operations to be suspended or neglected, and the effectiveness of drains to be reduced on this account. This will apply to numerous other enterprises where continuous operation is necessary. It is even applicable, but in a lesser degree, to a gravity outlet, it must be maintained in proper working order if it is to serve the purpose for which intended. It is possible to obtain reliable pumping machinery and to have it operated under competent supervision. For these reasons the objections to pumping are not considered serious. A plant for continuous operation, especially one of large capacity, should consist of several units. The total capacity of these should equal or exceed the maximum ordinarily required. During periods of low flow only so many units as are necessary need be operated.

CHAPTER VIII

CAPACITIES OF DRAINS

Drainage Runoff.—The term runoff, as applied to a given area means the amount of surface discharge from that area. It is the difference between the total amount of water reaching the surface and that absorbed or retained by the soils. The water retained by soils is not necessarily all absorbed by them; a large part may be held upon the surface and ultimately disposed of through evaporation. The natural runoff from an area is the quantity which it will discharge without artificial works intended to collect the waters which fall upon it. The factors which govern natural runoff from an area are first—the quantity of water reaching it, second—the power of the soils to absorb or hold water, and third—the manner or rate at which water reaches the surface. On steep slopes a heavy dashing rainfall, continuing for a short time only may practically all be carried away before the soils can absorb it; the same amount of water coming at a slow rate and continuing for a longer period may all be absorbed or evaporated.

Drainage runoff differs from natural runoff in that it includes also waters absorbed by soils or retained on the surface, which cannot be beneficially used by plants. From the viewpoint of capacity required, it may be regarded as the water which should be carried away by artificial works. It ordinarily includes both natural runoff and excess soil waters. Drainage runoff, from a given area, will generally exceed natural runoff because of this fact. The maximum discharges are also larger for the reason that better conditions are provided for collecting and discharging excess waters. This, however, may not apply to closed drains which surface or storm water can enter only by percolation through the soils.

In planning drainage works, for any given area, it is generally necessary, and always advisable, to make as close an estimate as is possible of the amount of water that will be developed. When closed drains are used, data regarding quantity of flow in them is necessary to determine the size of pipe required for a safe and

economic design; for open drains it is necessary, to determine the proper section of water-way. It is desirable also to know, within certain limits, the maximum discharge that may be expected to occur in open drains in order to provide suitable structures for them. It is to be understood that the many variable and indeterminate factors, which affect drainage runoff, make it impossible, to obtain exact quantitative results. The conclusions reached and the data upon which designs for drainage works must be based should, therefore, in many instances at least, be regarded as expressions of judgment rather than established engineering facts.

Factors which Determine Drainage Runoff.—As stated in the preceding paragraph, the quantity of water which a drainage system will discharge from a given area, assuming that such system is effective, is generally greater than the natural runoff from that area. This is due to the fact that on well-drained land, the excess soil waters are quickly drawn out and carried away.

In determining the factors which affect drainage runoff, some distinction must be made between lands supplied by natural rainfall and those supplied by irrigation. In the humid areas the amount discharged by drains is equal to the total rainfall, upon the soils, less the quantity disposed of by evaporation and plant growth and that lost through natural drainage. To illustrate this more fully, consider the soils of a given area at a certain time to contain a small amount of moisture, just enough to support plant life. Assume then that water falls upon the surface in an amount sufficient to more than saturate the soil to the depth of the zone of plant growth. Ordinarily a part of this water will find its way over the surface to drains, either natural or artificial, and be carried away without being absorbed by the soils. A part will pass downward below the zone of plant growth and also below the influence of drains and be carried away by natural drainage. The remainder will be absorbed and held temporarily by the soils. The water absorbed and held temporarily by the soils will part of it be drawn to artificial drains f they are available; a part will be taken up by plants and pass into the atmosphere through transpiration and a part will be disposed of by evaporation from the surface. By the continuation of this process, for a sufficient time, the soils are brought again to their original moisture content and the cycle of change is complete. Had the quantity of water which fell upon the surface been small,

for example, not more than the soils could absorb and retain, the increased moisture content of the soil would have been consumed by transpiration and evaporation only until the initial stage was reached. No water would have reached drains in the latter case for the reason that the entire supply would have been held by the soils until disposed of by plant transpiration and evaporation.

On irrigated areas the quantity that must be drained out of soils to protect them from danger due to a high water table, is also the excess above what can be disposed of through transpiration of plants, surface evaporation and natural drainage. The supply, unlike that of humid areas, is not distributed uniformly over the entire area tributary to a drainage system but is applied at different times and in different amounts to the various units of it. Some areas may not be irrigated at all, others may receive water but once or twice during the year, while some may have water applied to them at intervals of but a few days throughout the entire irrigation season. When the amount applied at one time is no more than soils will absorb, drainage for the removal of surface water is not required.

The subsoils of irrigated lands generally are relatively porous and natural underground drainage conditions more favorable than those found in the humid areas. These conditions permit of large quantities of water being applied at a single irrigation without causing surface runoff. They also allow ground waters to move with a great deal of freedom from one portion of an area to another. The needs for drainage are frequently found at some distance from the source of excess waters; in many instances lands needing drainage most have never been under irrigation. Seepage and water-logging generally are confined to portions of an irrigated area only; frequently, but not always, these portions are in natural depressions or near the foot of steep slopes leading to them. It is not possible in most instances to reach conclusions relative to drainage runoff from wet areas only; consideration must also be given to underground sources of supply coming from over irrigation or canal losses on higher lands. On uniform slopes the water table may rise near enough to the surface to cause damage over the whole of large tracts; this, frequently, is the result of overirrigation on the lands affected and the quantity of water applied to them is the principal source of supply to be considered in estimating the amount of drainage runoff.

Evaporation.—The action of evaporation is constantly going on wherever moisture is exposed to an atmosphere not already fully saturated. It has the effect of decreasing drainage runoff by disposing of a part of the waters which reach the soil. The amount of evaporation varies greatly for different localities and climatic conditions. The factors which contribute most to a high rate of evaporation are dry atmosphere, high temperature and wind movement. The laws governing evaporation have not been worked out sufficiently to permit of accurate theoretical determinations of the amount that will result under various conditions; quantitative data concerning it, consequently, must be determined from observations.

It is known that the highest rate of evaporation takes place in the hot arid regions. It is believed to be greater per unit of area of surface on small bodies of water than on large ones, due to the moisture laden atmosphere being carried away more rapidly in the former case. The records available show the highest evaporation in the United States to be about 115 inches per year. The highest per month is about 15 inches, or an average of approximately 0.5 inch per day. These are the results of observations taken in the hot arid regions of the southwest. They may have been exceeded in particular localities; the results are cited to give an idea of the quantities that may be disposed of through evaporation under certain conditions. For areas of lower temperatures, less sunshine, high atmospheric humidity, and little wind movement, the evaporation may be but a small part of that given above. Reliable data on the amount of evaporation for a particular locality can be obtained only by observations in that locality.

Evaporation takes place not only from a free water surface, but from moist soils also; the amount in the latter case depends upon the temperature of air and soil, the water content in the surrounding atmosphere and the quantity of water available in the top soil layers. Experiments generally seem to indicate that, under like conditions, evaporation from moist or even a saturated soil is less than from a free water surface.

Where free water exists at some distance below the surface, evaporation is limited to the amount of moisture carried up by capillary action. It is greatest when the surface soils are saturated and decreases as the water table lowers. When a depth is reached from which water is no longer carried to the surface by

capillary action, evaporation from ground water ceases. On account of the varying heights to which water will be raised in different soils it is difficult, if not impossible, to establish a general relationship between surface evaporation and depth of water table. From experiments made in Owens Valley, California, Lee[1] has shown that the amount of *evaporation decreases as the depth to ground water increases.* His results show also that, for nearly the entire range of capillary action, evaporation and depth to water table are approximately inversely proportional. The maximum depth from which evaporation in measurable quantities took place, as shown by these experiments, was about 7.5 feet; this seems to indicate that the soils were relatively uniform and of fine texture. As the height to which a liquid will be raised by capillarity varies inversely as the diameter of the capillary tube, it does not appear probable that the ratios between evaporation and depth to water table, as given above, would hold for soils composed of strata of different porosity or fineness.

On areas of permanently low water table, the effect of evaporation is limited to those times when the surface is wet from rainfall or from having water applied to it. When the water table is near the surface, as is frequently the case on irrigated areas, evaporation may play an important part in carryng excess water from soils. From the depths to water table on the different parts of an area and the rate of evaporation from each, it is possible to determine roughly the amount of water thus taken out of the soils.

Attention has already been called to the danger of soils becoming alkaline and unfit for cultivation due to evaporation of ground water, capillary action and evaporation as it is termed. It should be clearly understood that on thoroughly drained and properly cultivated soils, the bringing of any appreciable quantities of water to the surface through capillary action is prevented. Evaporation, on this account, cannot be considered as one of the means for disposing of excess soil waters. It may be used, however, in connection with drainage runoff to determine how much water is evaporated that should properly be removed by drainage.

Use of Water by Plants.—The term transpiration is ordinarily applied to the water which is carried out of soils by plants; it is the water which passes through plants during their

[1] U. S. Geological Survey Water Supply *Paper* No. 294.

growth. It is taken up by the plant roots from the soil, carried through the plant stem to the leaves and by them given off to the atmosphere. The amount of transpiration is ordinarily expressed in terms of pounds of water required to produce one pound of dry plant substance. This is sometimes called the transpiration coefficient. Results, which have been obtained by different investigators, vary greatly and range, generally, from about 300 as a minimum to about 600 as a maximum. From the wide variations in results, it seems probable that the transpiration coefficient varies for different plants and conditions of growth.

Various determinations have also been made of the amount of water that must be applied to soils for growing plants. This differs from the transpiration coefficient since it includes also the water evaporated from the surface of the soil. It is manifestly impossible to grow plants in a practical manner without losing a part of the water supply by evaporation. The amount so lost will depend upon the various factors affecting evaporation, and to some extent also upon how much the ground surface is protected from direct rays of the sun and air currents by the plant foliage. In many instances, also, especially where water is applied in large quantities at a single irrigation, some of it passes below the zone of plant growth and is lost. Results based upon quantities applied show that from about 600 to 1500 pounds of water are required to produce one pound of dry plant substance.

Rough estimates of the amount of drainage runoff may be obtained by deducting from the total applied to lands, the amount required for the growing of crops. The latter, on account of imperfect knowledge of the subject, cannot be definitely determined but an upper safe limit can ordinarily be assumed. A single example will serve to illustrate the method. The amount of dry plant matter per acre that an area is capable of producing may be fixed between certain limits. Assume, for the particular crop to be considered, that the upper limit is 8000 pounds. The maximum quantity of water that must be applied for this particular crop, as determined from the best data available, assume as 1000 pounds for each pound of dry substance. The total quantity of water required on this basis will be 8,000,000 pounds per acre, or a depth of about thirty-five inches. If more than this is applied, the excess must be evaporated from the surface

or removed by drainage, either natural or artificial. The above figures are not intended as a statement of the quantity of water required for any particular case but are given for the purpose of illustration.

Natural Drainage.—The term natural drainage, as applied to a given area, refers to the natural condition of that area for disposing of water from it. It is used both with reference to the surface, particularly topography, and to soils as regards porosity. Thus when it is said that an area is naturally well drained, it may mean that its surface slopes are such that water will flow off rapidly, or that its soils are such that water will pass rapidly through them. To make the term explicit, it is necessary to state whether surface or underground drainage is meant. Natural drainage, so far as it refers to topography only, has a marked influence upon surface runoff, but it may not effect, directly, ground water conditions. In other words, seepage, due to the presence of a high water table, is as likely to occur on or near slopes as upon flat areas. It depends upon whether underground conditions are favorable to it. Natural surface drainage conditions affect, in a marked degree, the rate at which surface waters will reach artificial drains, and consequently influence the maximum discharge that a given area will produce. For this reason, it is necessary that slopes be considered in determining the capacity of drains for carrying away surface waters. The size and outline of an area may also affect the amount of maximum discharge; that is to say the maximum rate of drainage runoff from a large area may be proportionally less than from a small one on account of the water, in the first instance, having farther to travel to reach a main drainage outlet. This is especially true if the flood period be of short duration. An area of compact regular form may also collect and discharge waters more rapidly than another of equal size but of irregular shape.

In determining the quantity of ground water that must be removed, natural drainage is an important factor. In some instances it is sufficient to carry away all of the excess waters which reach the deep subsoil strata, and thus make artificial drainage unnecessary; in other cases it serves to reduce the amount of artificial drainage required. Natural drainage, especially on irrigated lands, plays an important part in protecting soils from becoming water-logged and unfit for use.

It is frequently difficult to determine where underground drainage takes place and even more difficult to determine its amount. It is sometimes evident on a given area by the ground waters discharged from it to streams, or on to lands at a lower elevation. In many instances it will cause a lowering of water table during a dry period, or at times when water is not being supplied to lands. This change in the elevation of water table provides a means for estimating the quantity of water that drains out of the soil. If a represents the area in acres over which a lowering of ground water takes place; d the average amount of lowering in feet and v the percentage, by volume, of voids that are filled with gravity water or, in other words, the percentage of water that will drain out of the soils; then adv = the quantity in acre feet. If the lowering takes place during a given number of days t, then the quantity in acre feet divided by $1.98t$ gives the average discharge in second feet. It is necessary to bear in mind that a part of the lowering of a water table may be due to evaporation; this is especially the case when ground water is near to the surface. The amount of drainage that may take place through deep porous strata or fissures depends upon many unknown conditions; it is, for this reason, impossible to determine it with any high degree of accuracy; the above method, however, will serve for rough estimates in certain cases.

Maximum and Average Discharge of Drains.—The discharge of drains ordinarily varies greatly at different times; it is subject to periodic changes during the different seasons, and to irregular fluctuations resulting from long periods of dry weather or from excessive rainfall or application of water to soils. In some rather exceptional instances, the discharge is relatively constant throughout the year while in others it comes in the form of flashy floods followed by periods of little or no flow. No general relation exists between maximum and average discharges. The former represents flood flows only; the latter is a measure of the quantity discharged within a given period of time. The duration of flood flows varies greatly, some last for a few hours only while others continue for days or even weeks at a nearly constant rate. The discharge of drains required to remove surface water only is subject to greater variations than the discharge of those which draw their supply out of the soils. Steep slopes tend to increase the amount and shorten the period of duration of flood discharges.

The capacity of a drain should be based upon the estimated maximum discharge. It should be sufficient to remove the water which accumulates before it becomes a source of damage to soils or to crops. This sometimes requires a main outlet drain of a capacity greater than the maximum natural runoff from the area it is intended to serve. For open drains the capacities increase rapidly for increased depths of water carried. They consequently provide means for quickly discharging flood flows. When drains are filled to near the ground surface, they serve as outlets only and have little or no effect in removing ground waters from adjacent lands. They may even cause water-logging of land near to them if kept filled for long periods of time. To make a drain effective, and also to provide against its becoming a possible source of damage, the water in it, except during short flood periods, must be kept below the maximum allowable elevation of ground water. Its capacity while acting as a drain should be computed for that portion of the water-way which is below the elevation to which drainage is necessary; the portion above this should be considered only for flood discharges of short duration. The quantity that a closed drain will carry is necessarily limited to the capacity of the pipe or other conduit used. Closed drains, for this reason, are not as well suited for quickly discharging large flood flows as open ones. When the water which reaches a closed drain exceeds its capacity the drain becomes overloaded; the soils above it then tend to become saturated, and the drain is no longer effective for drawing water out of adjacent lands. An overloaded closed drain is similar to an open one when carrying more than its normal capacity.

Effects of Soils on Discharge of Drains.—The character of soils through which a drain passes determines, in a large degree, its rate of discharge. Whether the principal supply reaches a drain over the surface or by underground percolation also depends largely upon soil conditions. This applies especially to open drains and is an important factor in estimating the rate of discharge from them. Tight or semi-impervious soils absorb water slowly and a large part of the excess which reaches them finds its way over the surface to drains or natural water-ways; this results in a high rate of discharge for short flood periods. Pervious soils, if not already saturated, quickly absorb any water which reaches them and their drainage must be accomplished by drawing the excess out of the pore spaces. The resistance of the soil

reduces the rate at which water can reach subsurface drains and equalizes their discharge. When soils adjacent to a drain become saturated to a higher elevation than that of the water in the drain, there is, ordinarily, a percolation or flow out of the soil into the drain.

Rate of Flow Through Soils.—In its percolation through soils water must traverse the spaces between the particles. These spaces are very irregular in shape and much smaller than the particles themselves. The resistance offered by ordinary soils, or even by sands or gravels, is high and the flow through them very slow. The rate of flow also varies greatly for different soil conditions. Investigations and measurements that have been made show that it depends upon the slope down which the water travels, the size of soil grains, the percentage or volume of pore space and the friction between the particles of water or coefficient of viscosity. The rate of flow of water through different porous materials has been studied by various investigators and attempts have been made to express it by means of mathematical formulæ. These, when applied to materials that are relatively homogeneous. in character may give results sufficiently accurate for practical purposes. There is no known method by which the rate of water movement through heterogeneous soil masses can be computed.

Investigations show, for given conditions, that the underground flow or velocity varies directly as the difference in head or pressure, or in other words, the slope down which water travels. This was expressed by Darcy[1] in the form

$$v = k\frac{h}{l} \tag{1}$$

in which v represents the velocity of the moving ground water, h, the difference in head or pressure and l, the distance between two points in the line of flow; k is a constant depending upon the character of the material and other physical conditions. Hazen's[2] conclusions relative to the flow of water through sands are expressed by the following:

$$v = cdz\frac{h}{l} \quad (0.70 + 0.03t) \tag{2}$$

[1] Les Fontaines publiques de la ville Dijon, by H. Darcy, Paris, 1856.

[2] Some Physical Properties of Sands and Gravels, by Allen Hazen, *Report* Mass. State Board of Health, 1892.

FIG. A.—Making borings to determine character of soil and depth to ground water.

FIG. B.—Gravel stratum in bottom of drain showing freedom of water movement through it.

(*Facing Page* 102)

in which v is the velocity of water in meters daily moving in a solid column of the same area as the sand; c, is a constant whose value experiments indicated to be approximately 1000; d, the effective diameter of the sand grains (in millimeters); h, the difference in head; l, the distance through the sand that the water passes and t, the temperature of the water on the centigrade scale. The effective diameter of the sand grains of a given mass of sand is such that 10 per cent. of the grains are smaller and 90 per cent. larger than the effective diameter. He also introduces what is called the uniformity coefficient; this is gotten by dividing the diameter of the sand grain which is of such size that 60 per cent. of the material is of smaller grains, by the diameter of the grain which is of such size that 10 per cent. is of smaller grains, or the effective diameter. Thus if 60 per cent. of a sample be finer than 0.62 mm. and 10 per cent. finer than 0.25 mm. the uniformity coefficient is $\frac{0.62}{0.25}$ or 2.5. Hazen concludes that the data at hand only justify the application of the formula to sands having a uniformity coefficient below 5 and an effective size of grain from 0.10 to 3.00 mm. He states that for gravels above 3.00 mm. effective diameter friction varies in such a way as to make approximations of ground water flow through them very difficult. The velocity does not increase as rapidly as d^2 and for coarse gravels varies as the square root of the head. The influence of temperature is also less marked.

The following table shows the rate in meters per day at which water will pass through different sands with various heads at a temperature of 10°C. as determined by Hazen.

TABLE 4.—EFFECTIVE SIZE IN MILLIMETERS, 10 PER CENT. LESS THAN

h/l	.10	.20	.30	.40	.50	1.00	3.00
.001	.01	.04	.09	.16	.25	1.0	9.0
.005	.05	.20	.45	.80	1.25	5.0	45.0
.01	.10	.40	.90	1.60	2.50	10.0	90.0
.05	.50	2.00	4.50	8.00	12.50	50.0	
.10	1.00	4.00	9.00	16.00	25.00	100.0	
.50	5.00	20.00	45.00	80.00	125.00		
1.00	10.00	40.00	90.00	160.00			
2.00	20.00	80.00	180.00	320.00			

The relative quantities passing at different temperatures are as follows:

Degrees C.	Degrees F.	Quantity
0	32	.70
5	41	.85
10	50	1.00
15	59	1.15
20	68	1.30
25	77	1.45
30	86	1.60

Another formula which was derived by Slichter[1] for determining the quantity of underground flow is as follows:

$$q = 0.2012 \frac{pd^2s}{hnK} \tag{3}$$

In this q stands for the quantity of water, transmitted by the column of sand, in cubic feet per minute, s is the area of the cross section of the sand measured in square feet, p the difference in head or pressure measured in feet, h the length of the column measured in feet, d the mean diameter of soil grains in millimeters, n the coefficient of viscosity which varies with the temperature and K a constant whose value depends upon the porosity of the soil mass. In this expression p and h correspond to h and l respectively in Hazen's formula. The value of $1/K$ as computed by Slichter for porosities varying from 26 to 47 per cent. are given in the following table:

CONSTANTS FOR VARIOUS POROSITIES OF AN IDEAL SOIL

Porosity m, per cent.	$1/K$
.26	.01187
.27	.01350
.28	.01517
.29	.01694
.30	.01905
.31	.02122
.32	.02356
.33	.02601
.34	.02878
.35	.03163
.36	.03473
.37	.03808
.38	.04154
.39	.04524
.40	.04922
.41	.05339
.42	.05789
.43	.06267
.44	.06776
.45	.07295
.46	.07838
.47	.08455

[1] Motion of Underground Waters by CHAS. S. SLICHTER, U. S. Geological Survey, 19th *Annual Report*, Water Supply *Papers* Nos. 67 and 140.

The mean diameter[1] d or effective size is defined as that diameter to which if all the grains were reduced the resistance to flow would remain the same. It is determined by the use of the aspirator as suggested by Professor King[2] and by means of the following formula derived by Mr. Slichter:

$$d^2 = \frac{Kh}{spt}\ (.0877)$$

In this t is the time in minutes necessary to draw 5000 c.c. of air of temp. 20° through the soil, under an average pressure of p cm. of water at 20°. The constant K is to be taken from the table above given, d and h are to be measured in centimeters and s in square centimeters.

Slichter calls attention to the fact that in the formula for flow part of the expression on the right hand side depends only upon the character of the soil through which the water is passing. Representing this by k gives

$$k = 0.2012\,\frac{d^2}{nK}$$

and the formula becomes

$$q = k\,\frac{ps}{h}$$

If p, s and h, each be taken as unity, k is the quantity of water that is transmitted in unit time through a column of soil of unit length and cross section under unit difference of head at the ends. This is designated as the transmission constant of a soil. It is the rate per unit area that water will move vertically downward through a completely saturated uniform soil column.

The transmission constants for sands of various effective sizes of grains, and for porosities varying from 30 to 40 per cent. as determined by Slichter are given in the following table, No. 5. The results are given in cubic feet per minute.

Table computed for 60°F.; results for other temperatures can be gotten by the use of Table 6.

[1] The mean diameter of soil grains as used by Slichter is not defined in terms of the various-sized grains of which the soil is composed and for this reason cannot be gotten by the ordinary mechanical analysis. It does not correspond to the effective diameter as defined and used by Hazen.

[2] A New Method for the Mechanical Analysis of soils, by F. H. King, 15th *Annual Report* Agricultural Experiment Station, Univ. of Wisconsin, Madison, 1898, p. 123.

TABLE 5

Transmission constants from which the velocity of water in sands of various effective sizes of grain can be obtained.

Diameter of soil grain in mm.	30 per cent.	32 per cent.	34 per cent.	36 per cent.	38 per cent.	40 per cent.
0.01	0.000033	0.000040	0.000050	0.000060	0.000072	0.000085
0.05	0.000822	0.001012	0.001240	0.001495	0.001790	9.002120
0.10	0.003282	0.004050	0.004960	0.005980	0.007170	0.008480
0.20	0.01315	0.01620	0.01983	0.02390	0.02865	0.03390
0.30	0.02960	0.03640	0.04460	0.05380	0.06450	0.07630
0.40	0.05270	0.06480	0.07940	0.09575	0.1145	0.1355
0.50	0.08220	0.1012	0.1240	0.1495	0.1780	0.2120
0.60	0.1182	0.1458	0.1784	0.2150	0.2580	0.3050
0.70	0.1610	0.1983	0.2430	0.2930	0.3510	0.4155
0.80	0.2105	0.2590	9.3175	0.3825	0.4585	0.5425
0.90	0.2660	0.3280	0.4018	0.4845	0.5800	0.6860
1.00	0.3282	0.4050	0.4960	0.5980	0.7170	0.8480
2.00	1.315	1.620	1.983	2.390	2.865	3.390
3.00	2.960	3.640	4.460	5.380	6.450	7.630
4.00	5.270	6.480	7.940	9.575	11.45	13.55
5.00	8.220	10.12	12.40	14.95	17.90	21.20

TABLE 6

Variations of flow through sand for different temperatures. The quantity of flow at 60°F. is taken as standard; quantities at other temperatures are expressed as percentages of this amount.

Temperature	Per cent. of flow
32°F.	64
35°F.	67
40°F.	73
45°F.	80
50°F.	86
55°F.	93
60°F.	100
65°F.	108
70°F.	115
75°F.	123
80°F.	130
85°F.	139
90°F.	147
95°F.	155
100°F.	164

To use the transmission constants given by Slichter it is necessary to know the slope down which ground water is traveling the temperature of the water, the percentage of voids and the effective size of the sand grains. The first three of these can be determined ordinarily with little difficulty. The latter requires the use of the aspirator for accurate results and involves measuring the rate that air will pass through the sands while in their natural condition. The latter may, under some conditions, present practical difficulties.

Methods of Estimating Discharge of Drains.—There is no rigidly exact method by which the discharge of a drain can be determined in advance of its construction. Neither is it possible to determine the exact quantity that must be removed from a given area to effect its drainage. These questions are somewhat analogous to that of determining the amount of surface runoff that will occur from a given area but even more difficult than the latter for the reason that in estimating surface runoff some data regarding past experiences are usually available. Estimates on the quantity of water a drainage system will be required to discharge must be based upon results obtained from other somewhat similar areas, or from a consideration of the quantity reaching the soil and that disposed of through natural agencies.

The following methods may be used in estimating drainage runoff and the capacities of drains that will be required; the method best adapted to any particular case depends upon the nature of the data available and other conditions.

(*a*) By comparison with the discharge of drains on other similar areas where works have been constructed.

(*b*) By adding to natural surface runoff the amount of water that must be drawn out of soils to accomplish their drainage, together with additional amounts that may be developed due to more rapidly collecting excess waters by constructed works. The former of these will ordinarily increase the total quantity, and the latter the rate of discharge.

(*c*) By taking from the total quantity of water that falls upon or is applied to an area, the amount needed by plants and disposed of through evaporation and natural drainage. The remainder is the excess that must be removed by artificial means.

(*d*) By determining the amount of evaporation from wet or submerged surfaces of the areas to be drained.

(*e*) By estimating the amount that a drain will collect per mile, or other unit of length, from the particular soil in which it is constructed.

Discussion of Methods.—To estimate the discharge of drains from one area by comparison with that from another assumes that the two are similar so far as affecting drainage runoff. They must be comparable as to size and topographic features and both soils and subsoils must be of the same general character to insure like natural drainage from each. Careful and extended investigations are necessary to make a comparison of conditions on two different areas, and it is seldom that two separate and distinct tracts can be found that are alike in all of their principal features. This method of estimating drainage runoff cannot be used generally and when used liberal allowances must be made for differences in conditions that cannot be determined. The method is frequently well adapted to estimating and checking capacities for small subsurface drains which form a part of the same general system. In this case the results obtained from drains first built may be used in determining capacities of those intended for future construction. The method is not especially well adapted to large areas of varied topographic and soil conditions.

Natural surface runoff gives a basis for determining capacities of drains on areas of heavy rainfall and where large quantities of flow are involved. When these data are available over a sufficiently long period to give maximum discharges they may be regarded as reliable. It must be understood, though, that the construction of drains on an area increases the rate of discharge from it. The amount of this increase depends chiefly upon soil and topographic conditions and varies greatly for different areas. It is greatest where natural surface drainage is poor due to flat slopes and lack of depressions which will serve as waterways.

Maximum discharges for main outlets can be gotten by estimating the amount of surface water which accumulates during a storm period and computing the rate of flow necessary to remove it during a short enough time to prevent damage. This added to maximum natural discharge will give the total capacity required. The method is applicable to large flat areas subject to overflow and to swamps which are caused from excessive rainfall. Assumptions must necessarily be made relative to the time within which surface accumulations should be removed. It is manifestly impossible, in many instances, to carry away excess water as rapidly as it accumulates on large flat areas. It must, however, be removed quickly enough to prevent damage to crops

and soils. For ordinary farming operations damage, generally, will not result if excess waters are removed within a period of twenty-four hours. To this, however, there may be many exceptions and any unusual conditions must be given special consideration.

The amount of water which falls upon or is applied to an area serves as an index to the amount that must be removed through the combined action of natural and artificial drainage. The quantity that will be used by growing plants and carried off by evaporation, can be estimated, roughly at least, for any given locality. That which is disposed of by natural drainage is difficult, and in some instances, impossible to determine. If an area is underlaid by an impervious subsoil strata, as is sometimes the case, natural drainage from it may be measured as surface runoff; when, however, the subsoil is porous, water may escape through underground percolation in such manner that its amount cannot be estimated. In some cases the amount of underground drainage may be gotten roughly from the fall in ground-water table during periods when no water is applied or falls upon the surface. This requires a knowledge of the volume of soil pores. The method may sometimes be used also on irrigated lands where the quantity of water applied to them is known. In this case it is necessary to determine the rate of rise or fall of the water table in order that the amount which accumulates in the soil during a given period may be computed. When underground drainage is small, there is greater certainty in estimating drainage runoff than when it is large. The effect of underground drainage is to permit excess water to escape. The water table falls when the outflow exceeds the supply which reaches the soil and rises when the supply exceeds the outflow. The latter occurs during periods of heavy rain or excess irrigation. The quantity of water which accumulates in the soil due to rise in water table or in other words the quantity that must be removed to maintain equilibrium may be estimated from the rate of rise and area over which it occurs. Let a be the area in acres over which ground water rises, r the amount of rise per day expressed in feet, and p the percentage of voids in the soil, then arp represents the accumulations in soil in acre feet per day. This is the quantity that must be removed to prevent a rise in water table.

The amount of water evaporated from a wet area provided equilibrium has been established is a measure of the excess that

reaches the area. If the total supply which finds its way into the soil could be reduced by this amount the remainder would be disposed of by natural drainage and the ground water would be maintained at a sufficient depth to prevent appreciable evaporation from it. If it be assumed that conditions relative to supply and water requirements on an area will remain the same after drainage as before, evaporation represents the maximum quantity that should be drained out of the soils; this, however, will not be the case generally. In the humid areas the supply it is true, will remain the same. On irrigated lands additional water may have to be applied to supply moisture to the upper portion of the soil. This may be in excess of plant requirements and contribute to drainage runoff. The area before drainage may have been barren of vegetation so that evaporation took place from free water or from moist or saturated soil over the entire surface; after drainage it may be covered with deep-rooted vegetation capable of using a large part of the water formerly evaporated from the surface. This would tend to decrease the amount necessary to be drained out of the soil. There are some experiments of record which show, even in the arid regions, that the amount of water used by certain crops is as great as that evaporated from a completely saurated soil surface, generally, however, this does not appear to be the case. It does follow though that the water lost by evaporation from the surface of a wet area should equal or exceed that which must be drained out of the soil in order to reduce its moisture content sufficiently for successful cultivation. The only exception to this is the case where excessive irrigation is practised after lands have been drained.

The method of determining drainage discharge by the quantity of evaporation is applicable on many areas from which there is no surface runoff but which are kept wet by percolating waters reaching them. To determine the amount lost by evaporation in such cases it is necessary to consider the total area over which ground water is high enough to permit appreciable quantities being brought to the surface by capillary action. The portions where the surface is submerged completely saturated and where ground water is at different depths should be taken separately and the rate of evaporation from each determined and used in making estimates. The rate of evaporation varies for different localities and for varying depths of ground water and character

of soils. It is therefore necessary that it be known for the particular area under consideration before the losses by it can be determined.

The quantity of water per mile, or other unit of length, which a drain is estimated to collect in different soils may serve as a basis for determining the capacity of the drain. Such an estimate does not necessarily represent the total quantity of water that must be removed from a given area, but is rather an estimate of the quantity that can reach the drain. It may be regarded as a measure of the percolation constant of the soil in which the drain is constructed. Fewer drains are needed to remove a given quantity of water from a porous soil than from a relatively impervious one. The method is applicable to estimating the flow of individual drains rather than that of a system intended for the relief of a particular area. It is applicable also to drains constructed in homogeneous soils rather than those which contain porous strata in which large quantities may be developed. Estimates of the quantity of water per unit of length that a drain will develop may be made from the rate of flow through the soils adjacent to it. In making these estimates it is necessary to know the area of section or depth of the strata through which water percolates in its movement toward the drain. This for stratified or mixed subsoils varies greatly and consideration must be given to uncertainties of results on this account.

Any method of estimating drainage runoff involves the use of factors whose values cannot be accurately determined. Such estimates, for this reason, may be subject to wide variations from results obtained in actual practice. In draining for the removal of ground waters principally the tributary area from which they will be drawn is difficult to determine. It is frequently much larger than is indicated by surface conditions, and the drainage runoff, from a given area, may exceed the total surface supply which reaches that area. This is especially true where small tracts are involved.

Drainage Runoff from Irrigation.—On irrigated lands the volume of drainage water that must be removed depends largely, and in many cases wholly, upon the quantity reaching the soils through irrigation and from canal and lateral losses. Each particular case consequently involves a study of the canal and lateral system together with the character of soils, the quantity

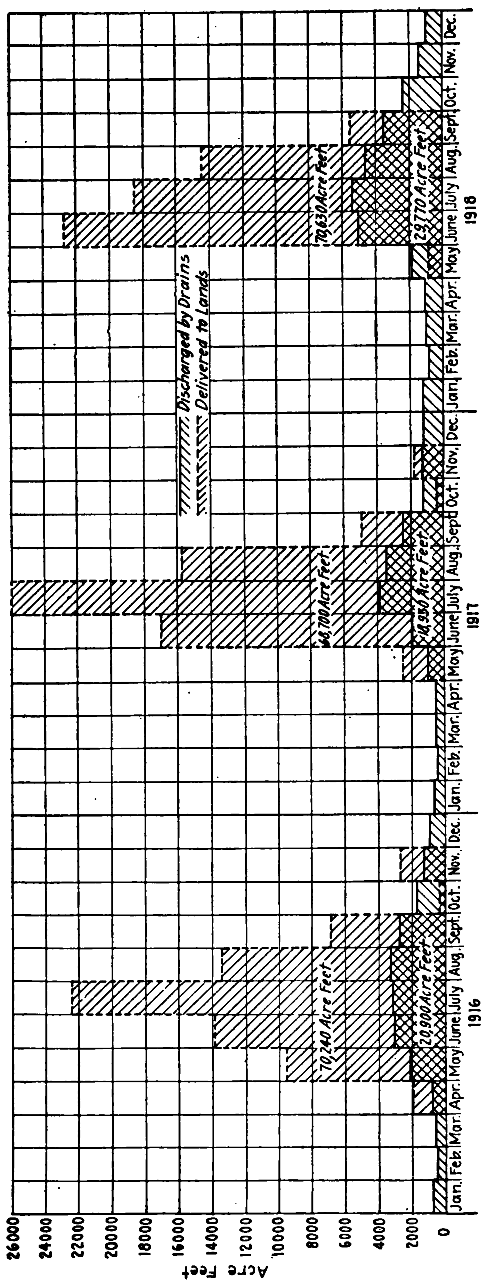


FIG. 16.—Diagram showing, by months, water delivered for irrigation, and discharged by drains. Shoshone project, Wyoming.

of water used and the manner in which it is applied.

Excessive irrigation, or the application at one time of more water than soils can retain may cause large drainage discharges for short periods. This is especially true in porous soils or sub-soils which allow free passage of water through them to drains. In less porous materials the same total quantity of discharge may occur at a relatively uniform rate over a longer period of time without producing high flood flows. In the latter case it is evident that a smaller drainage capacity will be necessary than in the former.

Losses from canals and laterals are sometimes sufficient in themselves to cause large flows in drains constructed in their vicinity. Such losses, generally, are confined to portions of a canal only and occur where it passes through sands or gravels or other porous materials. There is also, in most instances at least, a wide variation in the quantities of water which different reaches of a drain will

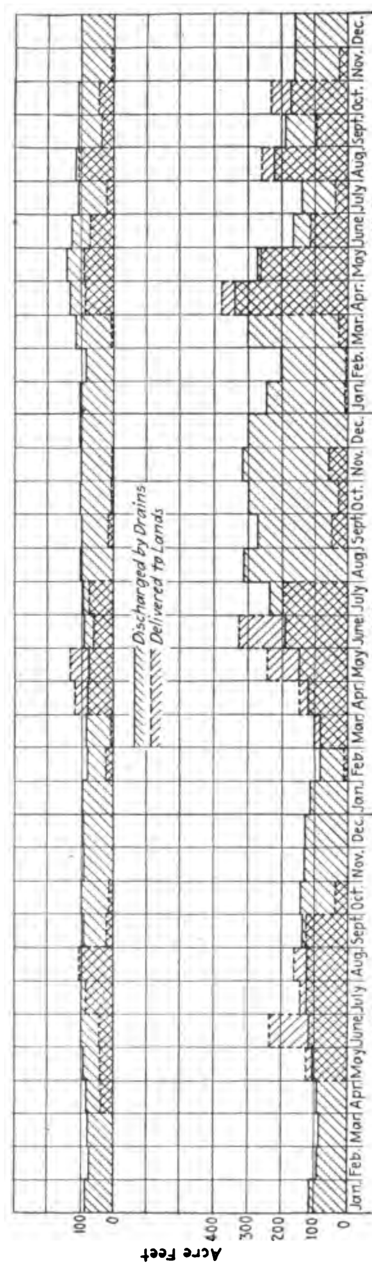


FIG. 17.—Diagrams showing, by months, water delivered for irrigation, and discharged by drains. Carlsbad project, N. M.

collect. The rendering of canals more nearly water-tight through natural silting or by artificial lining may materially change the quantity of drainage runoff.

The water discharged by drains is collected on but portions of the area under irrigation; these include the lower lands or those where soil conditions are favorable for the accumulation of ground waters. It is necessary, though, to consider the total tributary area in estimating the quantity of water to be removed. It is a common practice to express the latter as a percentage of the total applied to the land. This method is a convenient one and when applied to relatively large tracts or to the total area tributary to a drainage system gives fairly consistent results for like conditions. When, however, it is applied to the wet portions of an area only, the amount discharged by drains often exceeds that applied in irrigation. This is illustrated by the diagrams, Fig. 17. The areas here referred to were practically isolated but situated at some distance below other irrigated lands. The underground percolation which reached them from the higher areas carried drainage discharges far exceeding the water applied to the lands that were drained.

The quantity of drainage runoff from irrigated lands is so largely dependent upon character of canals and methods of applying water, that these are frequently controlling factors in drainage discharges. Where large underground losses are the result of excessive irrigation, or poorly constructed canals, they may be reduced or avoided by more conservative application of water or by the better construction of irrigation works. Experience seems to indicate that with proper use of water, the quantity necessary to be drained out of the soils will not exceed 25 per cent. of that applied in irrigation; and that in most instances it will be less than this amount. A drainage system capable of removing 25 per cent. of the water applied generally may be regarded as sufficient. When drainage requirements exceed this amount they should be reduced by applying less water to the land or by preventing excessive canal losses.

CHAPTER IX

DRAINAGE CONSTRUCTION

Location and Plans.—The making of locations and preparation of plans for drains, to be constructed, should follow next after investigations and studies of topography, soil and ground-water conditions. These preliminary investigations and studies should be thorough enough to definitely determine drainage requirements and show, generally, where drains are, or will be, required. Before beginning construction it is necessary that definite plans be prepared and the work laid out on the ground. Details which may affect the prosecution of the work should be settled, insofar as is possible.

The first consideration in determining the location of a drain is that it shall have a maximum effect in taking water out of the soil. It is necessary, also, that it be feasible of construction and maintenance at as reasonable a cost as is practicable. Examinations and surveys, of several different locations, may be necessary before one is found that will give efficient drainage, and at the same time, prove economically feasible of construction and maintenance.

Next in importance to selecting a suitable location is to determine the capacity required, and the type and depth of drain to be adopted. Plans for structures for the protection of the drain itself, or for lands adjacent to it, and crossings for roads, canals and other public or private uses must also be provided.

The alignment of a drain, generally, is of secondary importance to proper location for collecting water from the soil. It is necessary though in making locations to observe certain principles relative to alignment. Sharp curves in a drain tend to obstruct the flow and to cause cutting of the banks. The amount that flow may be obstructed or banks destroyed depends upon velocity and quantity of water carried. For a drain having steep slopes and intended to carry any considerable quantity of water, sharp curves should be avoided wherever possible. Where not possible to avoid them, protection works may be necessary to prevent erosion and consequent destruction of banks.

A drain of large dimensions should be as straight as possible in order to reduce its length and quantity of excavation to a minimum. It is sometimes economy to construct the lower portion of a large drain along the most direct route available, and to build secondary branches for the drainage of lateral areas not affected by it. This applies especially where ground water must be interceted at the foot of slopes whose courses are long and tortuous.

Surveys.—The general plan of making surveys, for location of drains, does not differ materially from that of other surveys, where alignment and profiles are necessary. The work requires the use of transit and level for obtaining locations and elevations, except in some instances where it may be advisable to lay out trial lines and obtain data for preliminary profiles without making transit locations. Where this can be done it may result in considerable saving of time and money. Final locations or even locations to be used for comparison should be accurately made first, to show their alignment and second, to permit of their being mapped and position shown relative to property lines and subdivisions. Drainage, especially in settled areas, necessitates obtaining rights of way over private lands, which may be highly improved, and an accurate location shown on a property map is necessary for this purpose. The location of drains projected upon contour or ground water maps are necessary also to show in a comprehensive manner the plan of a system.

Levels are needed to determine elevations and provide the necessary data for preparing profiles and determining outlet conditions. The same datum plane, or *O* elevation, which preferably is mean sea level, should be used throughout a system in order to facilitate comparison of elevations in any part of it. Generally this will have been selected as a basis for making preliminary surveys and investigations.

Profiles.—A profile of a drainage line should show first—the surface elevations and second—the character of material to depths that excavation is to be made. In making the surface profile it is not always practical to say, as is the case in some classes of work, that readings shall be taken and elevations plotted at definite intervals of say 50 or 100 feet. On very uniform slopes readings taken at intervals of 200 feet or more may be sufficient to give an accurate profile, while on broken and undu-

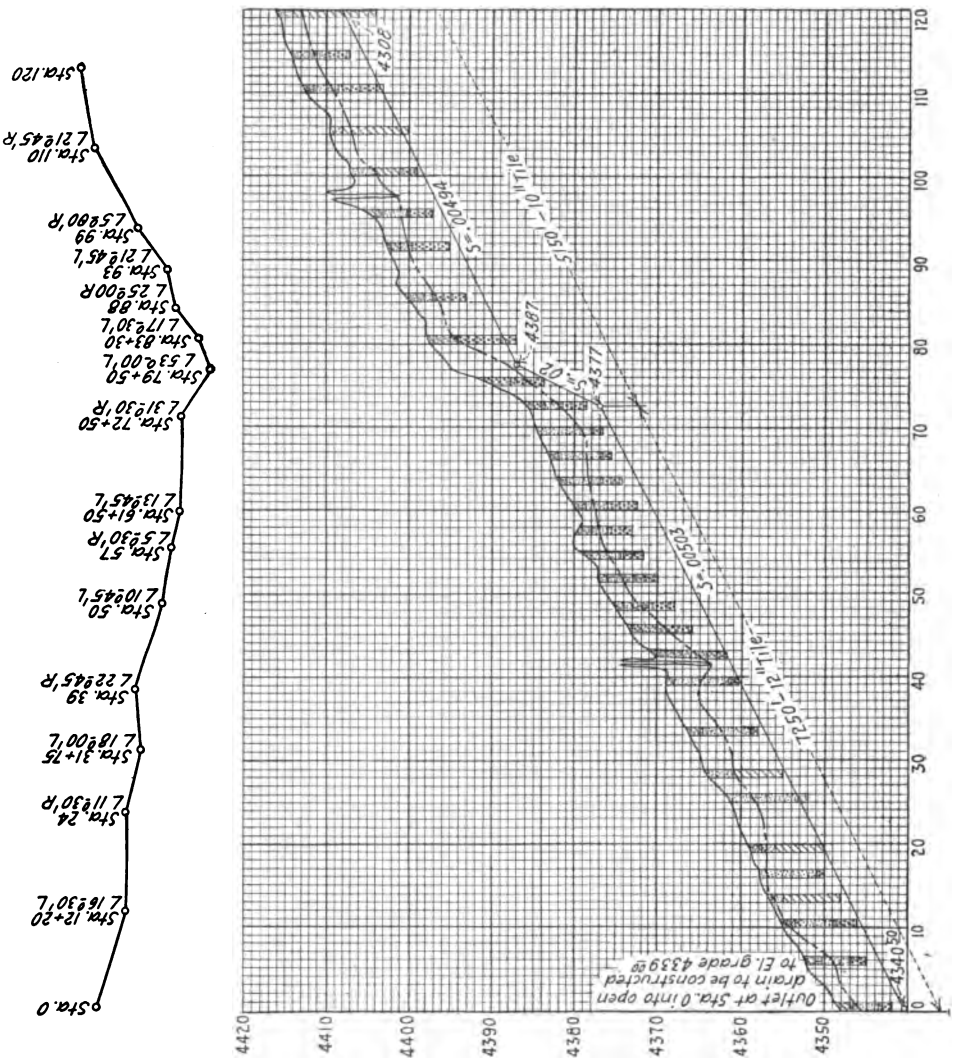


FIG. 18.—Profile and alignment of tile drain.

lating areas readings at intervals of 25 feet or less may be required. The important requirement of a profile is that it shall show accurately surface elevations along the line, and readings should be taken at sufficiently close intervals to meet this requirement. All depressions or natural water-ways which cross a drainage line may be important and should be shown.

The scale upon which a profile is plotted may be varied to suit different conditions and purposes. It should be large enough to show all necessary detail and no larger; any excessively large horizontal scale is cumbersome and does not give as comprehensive an idea as a shorter one. Scales which have been found generally satisfactory are from 500 to 1000 feet to the inch horizontal and 10 feet to the inch vertical. A convenient method of numbering profiles is from the lower end or in the direction that the work of surveys or construction of drains progresses. This method furnishes a ready distinction between drainage ditches and irrigation canals; on the latter work, proceeds from the upper end downward and profiles generally are numbered in this direction.

The character of soils should be shown either by logs of borings or test pits or by other suitable notation as described in Chapter VI. Profiles are intended, primarily, to show physical conditions along the line on which they are taken; they should contain the necessary data from which to determine proper grade lines or depths of cut and also the elevations of structures that may be required. It is important that the information which they give shall be accurate and complete.

Open Drains.—The open type of drain is applicable and may be used wherever the soil is sufficiently stable to permit of a channel being maintained in it. Some finely divided soils, especially when wet, have so little cohesion between the particles that they behave almost like a fluid. Banks will not stand in such materials except on nearly horizontal slopes and it is impractical, on this account, to maintain open channels in them. Drainage in such soils can be best accomplished by closed drains so protected that the fine materials cannot be carried into them. When an open drain can be maintained it is as effective as a closed one of equal depth. It is to be understood that depth here means the depth to water in the drain below the surface of the ground. The question whether an open or closed drain is better cannot be answered generally, and the selection of the one best

suited to a given locality frequently involves a consideration of many questions. One of the most important of these is the capacity required. Another is the value of rights of way and damage to property, which are greater for open drains than for closed ones. The costs of first construction and future maintenance are important factors; the cost of construction is generally less for open drains, and the cost of maintenance less for closed ones. Conditions may also be found where an open drain would be a menace to public safety and where a closed one must be adopted regardless of a consideration of cost.

The general principles involved in locating and preparing profiles apply equally to drains of the open and closed types. It is sometimes advisable that definite locations be made and the slopes that are available be determined before a definite decision relative to the type of drain can be reached.

Carrying Capacity of Open Drains.—The velocity of flow in open channels, from which capacity is readily obtained, may be computed by the use of Kutter's formula

$$V = c\sqrt{rs}$$

in which s is the slope r the hydraulic radius and

$$c = \left(\frac{\dfrac{1.811}{n} + 41.6 + \dfrac{.00281}{s}}{1 + \left\{ 41.6 + \dfrac{.00281}{s} \right\} \dfrac{n}{\sqrt{r}}} \right)$$

In this expression all of the factors except n are readily determined when the dimensions and shape of the section of channel are known. The value of n, which is commonly designated as the coefficient of roughness, depends upon the character of the water-way. It takes account of the resistance offered to flow by the roughness of bottom and sides, irregularities of shape, growth of plants and other deviations from a uniform smooth channel.

There are but few experimental data available on the coefficient of drains under actual working conditions and the values that must be used for n are consequently approximations only. The data available show that for water-ways in earth the value of n may vary from about .020 for perfectly clean uniform straight channels to .060 or more for irregular crooked and partially obstructed ones. For new channels of uniform section and in relatively firm materials the values of n range generally from about

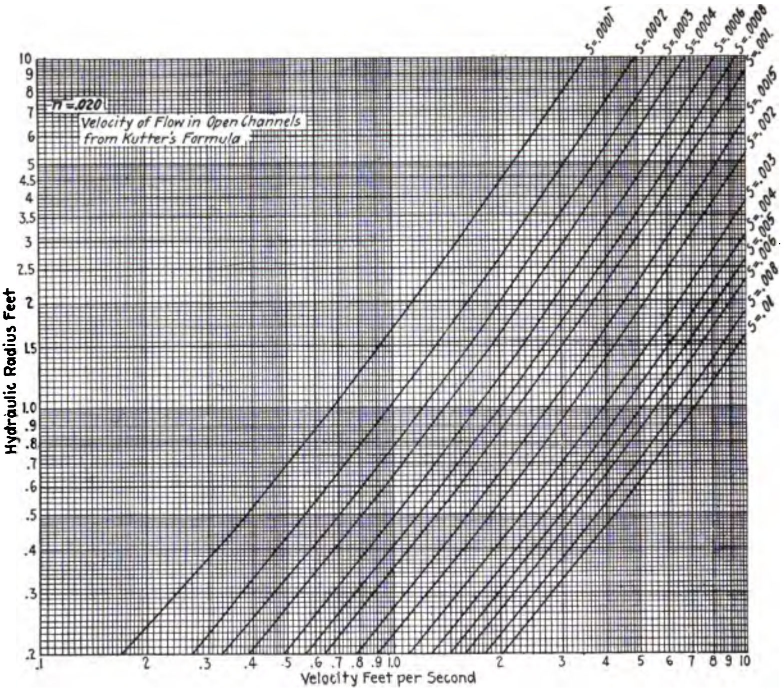


Fig. 19.—Velocity of flow in open channels.

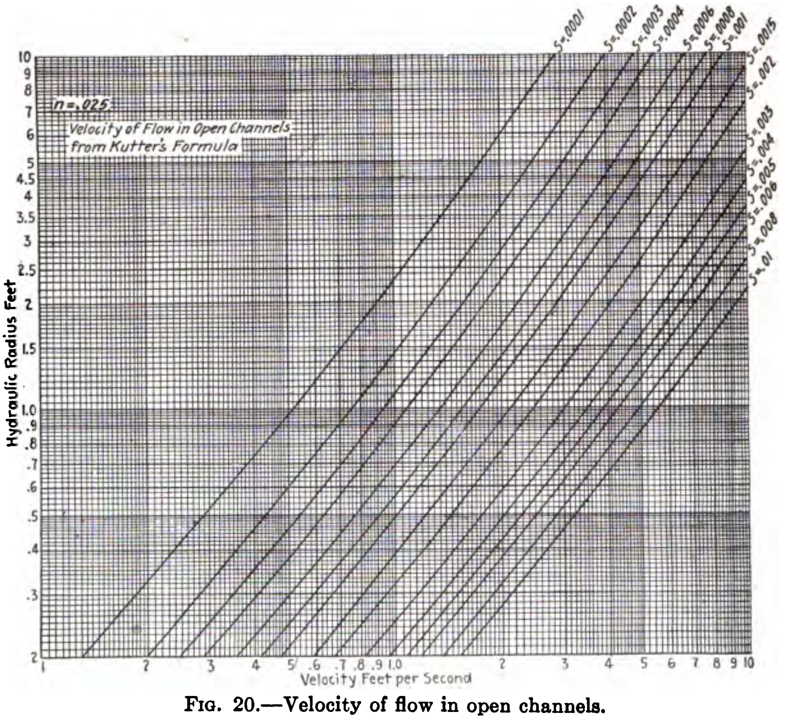


Fig. 20.—Velocity of flow in open channels.

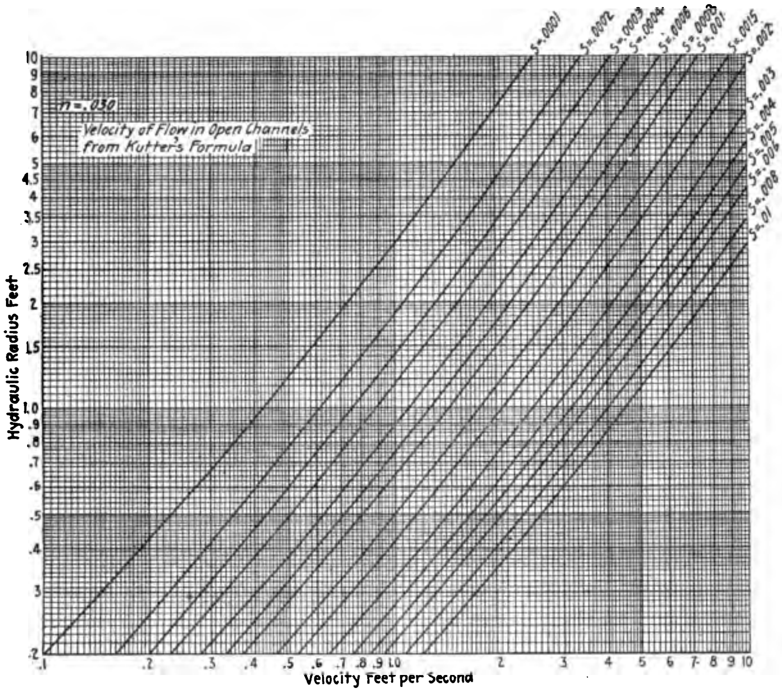


FIG. 21.—Velocity of flow in open channels.

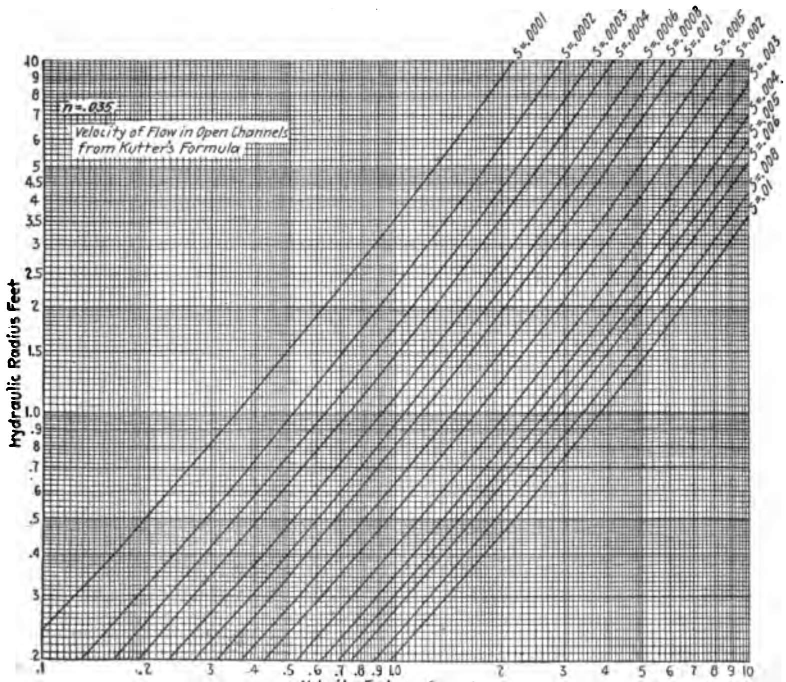


FIG. 22.—Velocity of flow in open channels.

.020 to .025. These values increase rapidly when erosion, sloughing of banks or growth of vegetation takes place. The carrying capacity of a drain, due to one or more of these influences will generally decrease with use; and it is good practice to provide for this by using a somewhat large value of n than is applicable to new channels or those in perfect order.

The velocity of flow for different values of rs and n are shown by the curves Figs. 19 to 22.

Section and Slopes.—The section of a drain must be large enough to give the carrying capacity required and also of such shape that it can be maintained in working condition. The latter requirement means that side slopes must be flat enough to have stability and prevent sloughing that will obstruct the channel.

Attention has already been called to the necessity of keeping the surface of water in a drain below the elevation of water table it is desired to maintain. It results from this that but a small portion of the excavated section is actually used as a water-way except during periods of flood discharge. Economy of construction consequently requires that this water-way be obtained with the minimum of excavation. This can be accomplished only by making steep side slopes; stability of banks, however, frequently requires that these be made relatively flat. There is no general rule by which the most advantageous section can be determined, it must be based upon the conditions and requirements of each particular case. The capacity that a drain shall have and the depth below ground surface that water is to be maintained in it, are necessary and must be determined before the section is designed. The problem is then to determine the section best adapted to suit requirements. In firm materials that will withstand erosion and sloughing of banks a narrow and deep water-way is generally the most economical of construction and maintenance. Such a section gives a greater velocity for a given slope and quantity of flow, than a wide and shallow one. The narrow channel also offers less opportunity for the growth of plants which tend to obstruct the drain. In unstable materials the sloughing of side slopes may cause a partial filling of the water-way and reduce the effective depth of drain. Where this is the case the maintenance of a narrow deep channel may be impracticable. Where the water-way of a drain is excavated into soft saturated material—semifluid in character—the bottom

FIG. A.—Lining canal with concrete to prevent water losses and protect adjacent lands from seepage and alkali. Carlsbad, N. M.

FIG. B.—An open drain with shallow water-way. A source of seepage and consequent menace to adjacent lands.

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PLATE VIII

FIG. C.—Open drain with water-way a safe depth below the surface.

FIG. D.—Erosion of banks on an open drain; the result of excessive slope.

may be pushed upward by the weight of adjacent banks. This condition generally can be minimized, and sometimes prevented, by using a wide channel with flat side slopes so as to reduce the weight of banks immediately adjacent to the excavation.

The section of a drain should be as uniform as is practical. The excavation should be made to prescribed lines, and variations therefrom should be made only where required, by a different class of materials, to make banks stable or to avoid excessive excavation.

The slopes of a drain is the ratio of its fall to its length; this is commonly expressed as a decimal. For example if the fall is one foot and length 500 feet the slope $-s = \frac{1}{500} = .002$. The maximum slope that a drain may have generally cannot greatly exceed the surface slope of the area through which it is constructed. It is sometimes practical, however, to give a greater slope than that of the surface by deep cutting at the lower end. This applies especially to a relatively short drain, and is of little value for a long one on account of the excess depth required in the lower portion, to materially increase its total fall.

The slope of a drain should be as steep as natural ground conditions will allow, up to the limit that the channel will stand, without damage by erosion. The latter depends upon the character of material forming the channel and the quantity to be carried. Uniformity of slope is an advantage for economic and efficient maintenance, since where it varies from point to point there is a tendency to erosion on the steeper portions and a filling on the flatter ones. This is especially true when the fall is large, and in such cases economy of future maintenance frequently justifies increasing the amount of excavation in order to obtain uniform slopes.

Staking Out Work.—It is too frequently assumed that the building of a drain involves only the excavation of a channel and that it is unnecessary to work to definite lines and grades. This method frequently leads to an excess of excavation in one place and a deficiency in another; it may increase the cost of the work, above what it should be, reduce the efficiency of the drain, make future maintenance more difficult and finally leave an unsightly job. In order that a drain may be excavated to an accurate section in a workmanlike manner it is necessary that it

be accurately laid out on the ground. The center line should be located, the line of slopes should be determined and marked on the ground as a guide for the beginning of excavation. The depth of cut below these slope stakes should also be shown in such manner that they can be readily referred to during the progress of the work.

The method of staking out drains does not differ from that used for irrigation canals or for earth work generally. After a profile has been prepared and the grade line established the depths of cut, on center line, at stations 50 or 100 feet apart should be determined. From these the location of the top of slopes may be obtained by the ordinary methods of cross sectioning. This work, when completed, furnishes necessary data for computing the amount of excavation. In staking out work for construction it must be remembered that all material within the section of the drain will be removed and that reference stakes must be placed outside the slope lines to prevent their being destroyed.

Excavation.—The work of excavation embraces the greater part of that to be done in the construction of open drains. It includes the cutting of drainage channels, the building of any embankments that may be required for protection or for roadways and the backfilling around structures. In connection with excavation the engineer, in addition to establishing lines and grades and staking out work on the ground should have supervision of construction, which includes methods of doing work, variations or changes in plans that may be found necessary, disposal of excavation and the measurement and classification of materials. Supervision of the methods of doing work is necessary for economic results; inspection is needed to insure the excavation of drains to the required section, and the disposal of material in a proper manner. Measurements and classification of the excavation is necessary to determine unit costs, rate of progress and to provide a basis for payment when work is being done by contract.

The work of excavation should be covered by definite plans and specifications, to serve as a guide in the prosecution of the work and also as a basis of agreement if work is performed by contract. Specifications should cover all ordinary questions that may arise relative to the work to be done.

Methods of Excavation.—Drains are commonly excavated by hand, by teams and by the use of machinery, depending upon

the character and amount of work to be done. Excavation by hand is limited generally to drains of small dimensions; to attempt large works by this method would be impractical and the cost prohibitive. Excavation by teams is limited to the handling of such materials that animals can work in without becoming mired, and to drains of such size, and shape of section that it is practical to draw the material out of them. On account of the limited amount of work that can be done by hand or team methods, machinery is necessary for economic results on drains of any considerable size. The dimensions of a drain and character of excavation to be removed determine the type and size of machine best suited to it.

The machines used for drainage excavation are of two general types, namely: floating machines—or dredges, as they are sometimes called, and land machines. Each possesses advantages for particular conditions and in some instances the one is especially suited to work that cannot be done with the other. Floating machines require a constant supply of water for their operation and to provide means for their being moved as work progresses. They can be used in soft materials over which it would be impractical to move a land machine; they are for this reason specially adapted to flat swamp or overflow areas where large channels are required and where the boggy nature of the soil would make excavation by any other type of machine difficult or impossible. On account of their lack of portability except through an open water-way, they are not suited to small detached jobs. Floating machines may be equipped with buckets of either the dipper or clam-shell types, or they may be provided with suction equipment.

Land machines, generally, are suited to all materials that are sufficiently stable to support the machine and make its transportation over them feasible. The various types and sizes of these machines make them suitable for large and small drains and for different materials that may be encountered.

The principal factors involved in the efficiency and economy of a machine are its rate of working, cost of operation, depreciation and repairs, and the percentage of time that it can be kept in actual operation. The suitability of a machine for each job must also be considered. It may be too large or too small for the work to be done in a specific instance. If too large its first cost and expense of moving to the work may result in exces-

sive costs; if too small its progress may be so slow that overhead charges will increase the cost above what is reasonable. A machine may be capable of a high output of work at a reasonable cost if kept constantly in operation, but uneconomical under conditions where it cannot be used continuously.

One of the important factors in drainage excavation is the expense and loss of time required for moving. This applies not only to moving from job to job but also to the shifting of the machines from point to point during the progress of work. Where drains are small or even of medium size a machine which can be quickly and cheaply moved is necessary for economic results. On large channels where but little moving is required portability is of less importance.

Land machines are of various kinds and are equipped with buckets of the dipper, clam shell and drag types. With the dipper bucket the machine operates behind the excavation in order to provide a face against which the bucket may work; with the drag bucket the machine must work ahead of the excavation. The latter type has advantages over the former; a greater variety of shapes of section can be excavated with it, the range for the disposal of excavated material is greater and it can be kept on ground that has been undisturbed and at some distance from the excavation. The latter is especially desirable in soft materials or where it is necessary to go over work the second time. Generally the dragline excavator has proven well adapted for drainage work, and it is extensively used for that purpose. The portable types of this machine are especially well suited to small and medium-sized ditches on account of the ease and rapidity with which they can be moved.

Disposal of Excavated Material.—The disposal of material excavated from open drains sometimes requires special consideration. The large masses of earth if piled in high irregular ridges along the drain are unsightly and soon become a seeding ground for noxious weeds which are a menace to adjacent lands. Earth piled immediately adjacent to a drain may be washed into it or it may cause a caving of banks due to the extra load it imposes upon them. It is also an obstacle to future maintenance since it prevents free passage along the drain. If the excavated material is leveled down, the cost of work is increased and greater property damages may result on account of extra rights of way required.

It is necessary to consider indirect damages resulting from an unsightly job, and obstacles to future maintenance, and to compare them with extra cost of first construction. The damage due to high spoil banks is, in a measure, a sentimental one, but becomes real when it affects property values. Any obstacle to keeping drains in proper working order, or any obstruction which makes the work of maintenance more difficult affect directly the value of the system either by making it less efficient or by increasing the cost of keeping it in proper working order. The proper maintenance of a drain is so important that it should be given consideration in the original plans of construc-

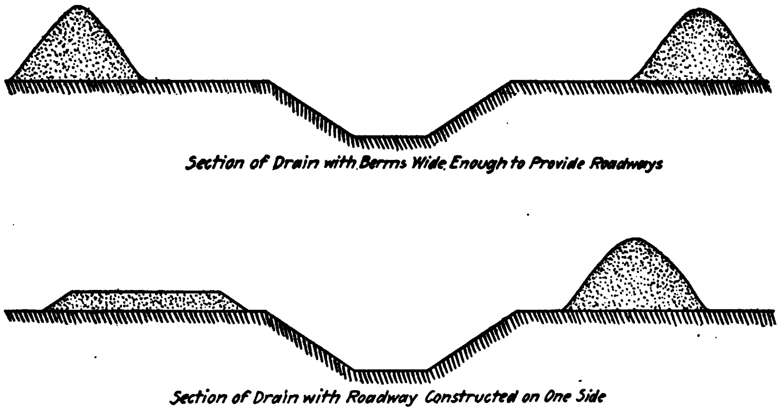

FIG. 23.—Drain with roadway on bank.

tion. Cases may be found where little or no artificial maintenance will be required as for example where the channel is in firm material that will withstand erosion and where slopes are steep enough to insure the carrying of sediment out of it. These conditions are exceptional.

It is necessary for proper maintenance of a drain that provisions be made for moving machinery or other equipment along it; also that space be provided for the disposition of material removed. One method of making a drain accessible is to leave a berm between it and the spoil bank, wide enough for the passage of teams, machinery, and other equipment. Another is to level down the spoil bank sufficient to form a wide roadway, Fig 23. This has an advantage over the berm as it disposes of high banks which are always objectionable and also makes it possible to deposit additional material on the outside of the bank.

Roadways not only provide means of travel along drains for maintenance purposes but are valuable also for inspection and may serve as avenues of transportation for many purposes. The material excavated may be deposited on both sides of the drain, or it may all be disposed of on one side depending upon many conditions. It is good practice to form an embankment on the upper side of a drain sufficient to prevent lateral drainage being discharged over the slopes into it. This should be collected and carried to points where it can be taken into the drain through suitable structures.

Excavation in Saturated Material.—Difficulty is frequently experienced in excavating drains to the required depth when material taken out is in a saturated condition. Some soils, when wet, have so little cohesion between particles that slopes will not stand to any considerable height in them. These same soils when dry may be relatively stable and drains may be maintained in them without special difficulty. Soils consisting of sand mixed with silt and also some almost pure sands are of the character described and drains cannot be excavated in them to but a shallow depth below the ground water table on account of material coming in as fast as it can be removed. Any attempt to force the excavation to grade, by removing excess quantities, is likely to cause a sloughing of banks which will completely destroy the section of drain.

Excavation, under conditions described above, can generally be accomplished by doing the work in successive stages. The drain is at first excavated as deep below the water table as can be done without causing sloughing or drawing in material from the sides. It is then allowed to stand until ground water in the soils adjacent is lowered and banks allowed to drain. A second cut is then made and the process of gradually drawing down the water table and draining the banks is continued until the required depth is reached. Generally, a second cutting is all that is required for drains of ordinary depth.

For the first excavation which is intended, primarily, to lower the water table along the line of drain, either the full width of section or a narrow cut along one bank may be constructed. This, however, should be wide enough to carry the quantity of water developed without producing an excessive depth of flow.

Closed Drains.—A closed drain has two principal advantages; it permits the use of land upon which it is constructed, and is

FIG. A.—Sloughing on an open drain, the result of saturation and unstable material in banks.

FIG. B.—Excavating open drain with drag line excavator, Yuma Project, Arizona.

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PLATE IX

FIG. C.—Excavating open drain with steam shovel, Shoshone Project, Wyoming.

FIG. D.—Excavating for tile drain with drag line excavator, Shoshone Project, Wyoming.

not subject to the same deterioration, in efficiency, due to a decrease in depth as an open one. Of these advantages, the first is probably the more important since it is possible generally to maintain the depth of an open drain by proper care. A closed drain does not have the same range of application as an open one on account of its limited capacity. The cost of a closed drain, of large capacity, is high and it may be impractical on this account.

Closed drains may be constructed of various materials, but as a rule they are made of clay or cement pipe or from wooden boxes; the latter is generally unsatisfactory on account of the tendency of wood to decay rapidly when placed where it is alternately wet and dry which may be the case with a drain. For this reason wood should be used only where it is impractical to get more permanent material at a reasonable cost. The use of cement pipe must be carefully considered in sections of the arid region where soils contain alkali salts which disintegrate cement. Vitrified clay pipe is not affected by alkali or other soil constituents.

Closed drains should be of a permanent character; this requires that the material of which they are constructed be lasting and that they be so built that they can be maintained in an operating condition continuously. When a drain refuses to operate and water is permitted to stand in the pipe there is danger that it may become silted or displaced and permanent injury done to it as a result. It is difficult and expensive to repair a drain should it become obstructed while carrying a large flow.

Alignment and Slopes.—The alignment of a closed drain should be free from curves; changes in direction in it should be made by means of angles at the points of intersection of tangents. These points should be marked and permanently protected so they will serve as a means by which the location of the drain can be readily found. If a closed drain is built on curves, as is an open one, it cannot be so readily located for repairs, should they become necessary. A pipe line, laid on a tangent, will hold its alignment better and joints can be made more secure against sediment washing into them than one laid on a curve.

The slope of a closed drain should be as great as the natural fall of the country will allow in order to give it a maximum carrying capacity and also greater assurance against sediment being deposited in the pipe. Danger of erosion need not be considered.

The minimum slope that may be used successfully depends somewhat upon the size of pipe; it is less for large sizes than for small ones. It should be great enough to remove fine sediment that may find its way into the drain. Experience has shown that a slope of about one foot per thousand is the minimum that should be used for drains of twelve inches in diameter or less. With a slope less than this, the velocity is slow and carrying capacity is small.

When it is necessary to change from a flat slope to a steeper one in going upstream a trap box should be placed at the point of change. A pipe of sufficient size should be used on the flatter slope to give a capacity equal or greater than that above. This will prevent the possibility of the lower portion becoming overloaded by water from above.

Size of Pipe.—The size of pipe required depends upon the slope and amount of drainage runoff. The capacity of a pipe may be computed by means of Kutter's formula, in the same manner at for open drains, by using a proper value of n. This value depends upon the character of the interior of the pipe. The smoothness of the interior walls, the number and evenness of joints, and variations in the size and shape of individual tiles of which the line is composed, all have an influence on the velocity of flow. A line constructed of pipe with smoothly trimmed ends has a lower value of n than one in which the ends are left rough.

On account of the many factors which influence flow it is impossible to give a value of n that will be applicable to each particular case. The somewhat meager data that are available on the subject show, for well constructed tile drains, values of n ranging from .012 to .015. These values are for lines where the interior of the pipe is smooth, and true to shape and where joints are carefully made so as to eliminate sharp angles or projections which will retard the flow.

Small pipes are more liable to become plugged due to silting or slight displacement than larger sizes. On account of their low velocities even on relatively steep slopes they have but little capacity, and are not suited to conditions where flood discharges may occur. For example a pipe of .4 foot (about 5 inches) diameter laid on a slope of 1 foot per thousand and having a value of $n = .015$ gives a velocity of only .94 foot per second. For deep drains the item of pipe is but a small part of the cost and increasing the size does not add an appreciable amount to the

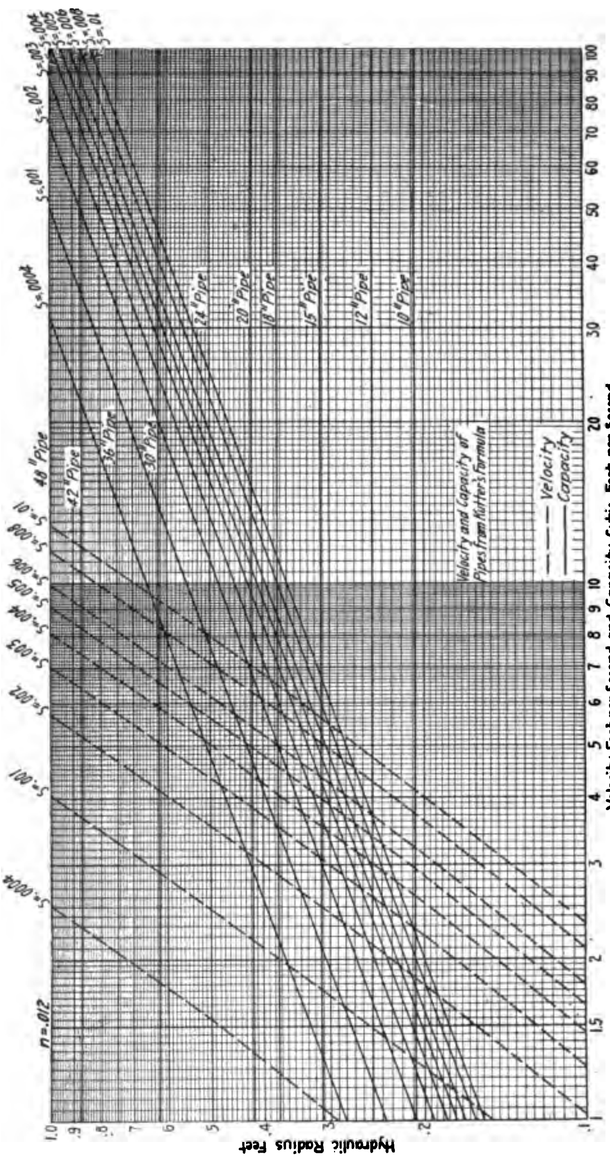

Fig. 24.—Velocity and capacity of pipes.

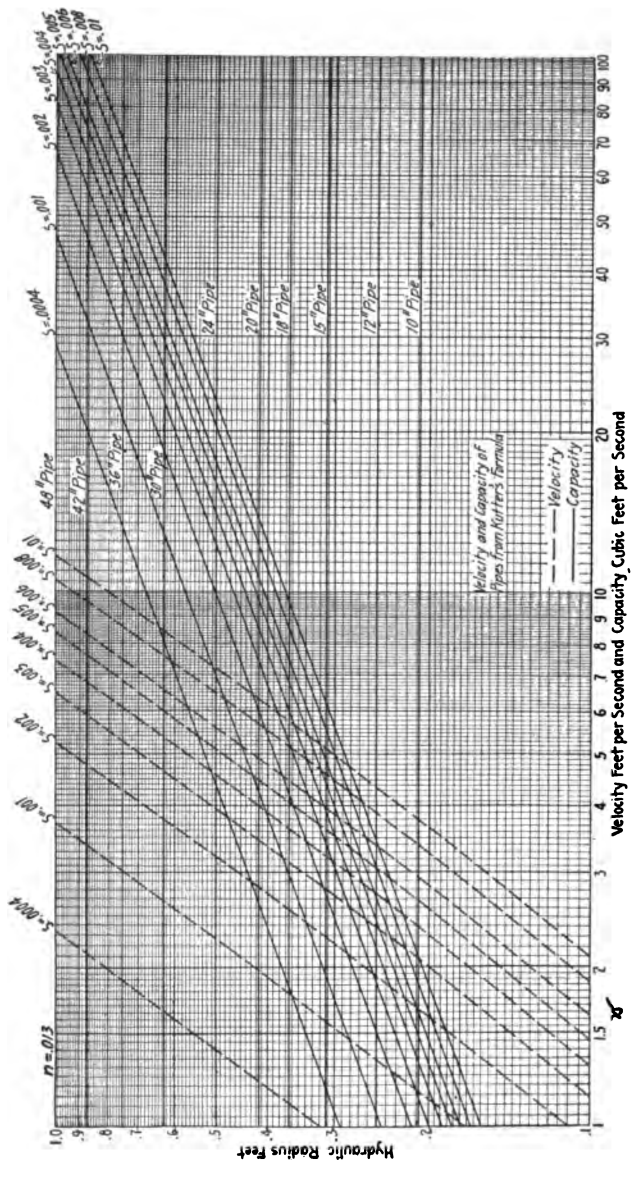

FIG. 25.—Velocity and capacity of pipes.

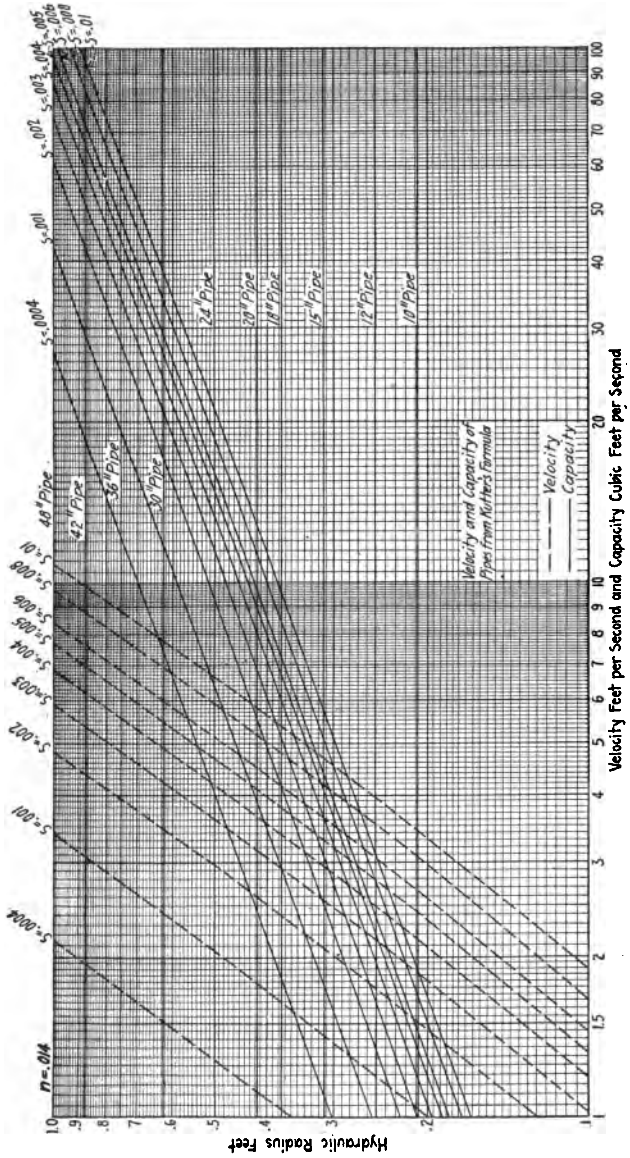

FIG. 26.—Velocity and capacity of pipes.

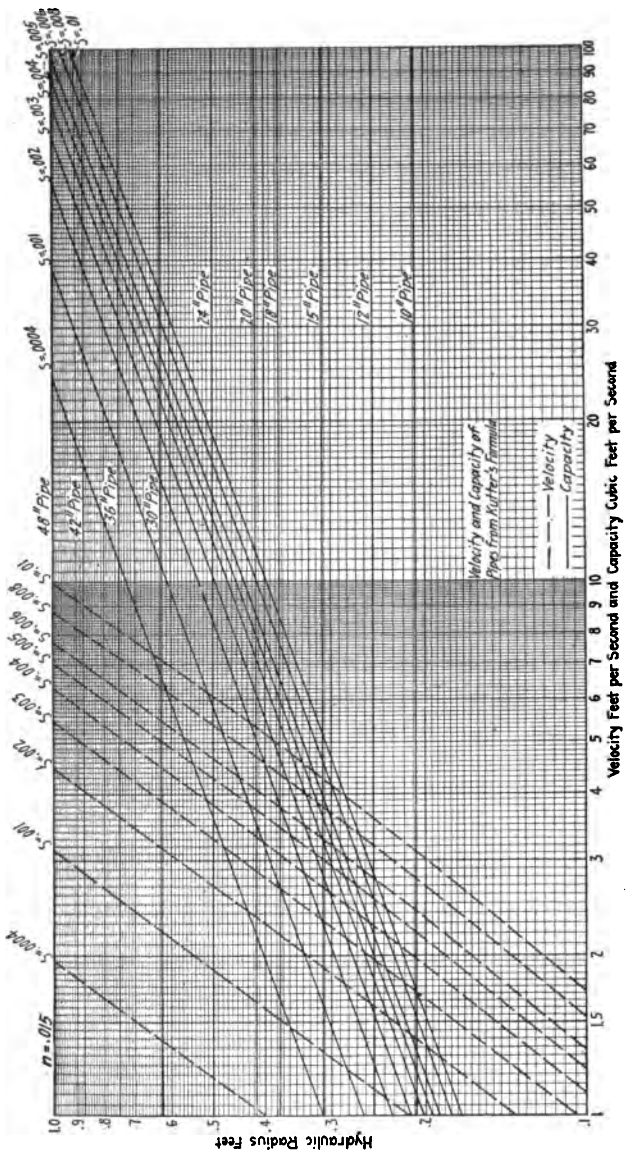

FIG. 27.—Velocity and capacity of pipes.

total expenditure. For the above reasons the feasibility of using small pipe, that is sizes of say less than 6 inches in diameter generally may be questioned. For drains such as are usually required on irrigated lands the minimum should be still larger.

For velocities and carrying capacities of closed drains see curves, Figs. 24 to 27.

Foundation and Covering for Pipes.—One essential requirement for a tile line is a foundation that will hold the pipe securely at grade. Settlement, even though small, tends to open the joints and permits material to be more readily carried through them. The washing away of earth surrounding the pipe leaves it unsupported and in a condition to be easily broken or displaced. Some materials such as firm gravel, shales and even hard clay which will not erode, are generally sufficient to support tile; in light materials such as loams or fine alluvial soils some form of artificial support is necessary, ordinarily, to prevent settlement.

A suitable foundation may sometimes be made by means of gravel or broken rock placed in the bottom of the trench. The quantity of gravel or rock used must be sufficient to support the pipe and the load of covering which it carries. Another plan of foundation which has proven satisfactory is a wooden cradle so constructed that it offers resistance to settlement and also to the pipe being moved out of line. The pipe is supported at or near the quarter points, that is on lines approximately 45 degrees above the bottom. A pipe so supported offers greater resistance to crushing than when laid on a flat surface. There is little danger of the destruction of the wood through decay for the reason that it is placed practically below the grade of the pipe where it is kept saturated while the drain is in operation.

In very soft material it is sometimes necessary to provide a large bearing area for the foundation; this may be done by means of long cross planks placed under the stringers which support the tile. In a few exceptional cases it has been found necessary to support the rack, or cradle, on piles driven into firm material at some depth below the grade of the drain. The wooden foundation should be brought accurately to grade in the trench before the tiles are placed upon it. This greatly expedites the work of laying pipe which balances, in a large degree, the cost of material and work of placing the foundation.

Tile should be surrounded by porous material, such as gravel or broken rock, that will not erode or permit fine sediment being

carried through it. Water should be admitted to the pipe through the bottom portion of the joints only, the upper part of

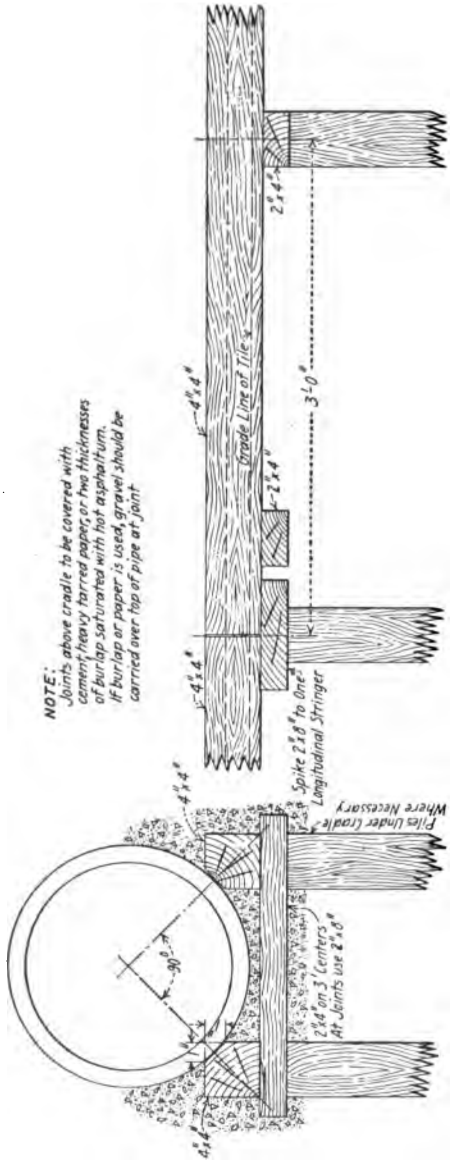

Fig. 28.—Wooden cradle for supporting tile, also piles for supporting cradle in very soft materials.

the joint should be closed by means of a flexible covering which may consist of heavy tar paper or burlap saturated with asphal-

tum. This covering should be from three to four inches in width and at least two-thirds of the outer circumference of the pipe in length. It should be put on after the pipe is in place and carefully protected from being displaced while the pipe is being covered.

Trap Boxes.—Trap boxes are intended to serve the double purpose of collecting the sand and sediment carried by a drain and also to provide access for inspection. They should be placed not more than 1000 feet apart and in fine soils which erode

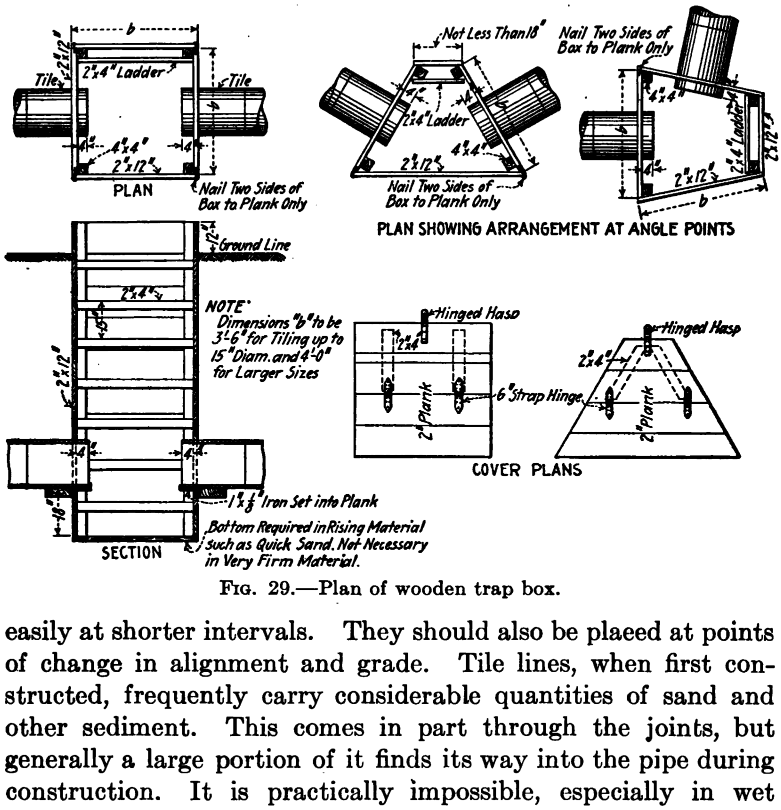

FIG. 29.—Plan of wooden trap box.

easily at shorter intervals. They should also be plaeed at points of change in alignment and grade. Tile lines, when first constructed, frequently carry considerable quantities of sand and other sediment. This comes in part through the joints, but generally a large portion of it finds its way into the pipe during construction. It is practically impossible, especially in wet mucky material, to keep a pipe free of sediment while it is being laid. It is necessary that this be washed out before the drain can operate to full capacity. If all the sediment, which finds its way into a drain, is carried through to the outlet there is danger of the flow being obstructed by it and a clogging of the drain result. This is especially true where there are changes from steep to flatter slopes.

Trap boxes may be built of wood or more permanent materials such as cement or brick; they should be large enough to allow a man to enter them for the purpose of removing sediment and for inspection. For ordinary tile lines 4 × 4 feet is a convenient and satisfactory size for trap boxes. The bottom of the box should be from twelve to eighteen inches below the grade of the pipe in order to provide space for sediment to collect.

Where the slopes of drains are steep enough to permit, it is good practice to provide a small drop at each trap box. This raises the lower end of the inlet pipe above the water surface in the box and gives it a free discharge.

Trenches for Closed Drains.—The width of a trench in which tile is to be laid should be as small as is practical in order to reduce excavation to a minimum. A trench, however, should be wide enough to provide room for men to work in it and allow the pipe to be brought accurately to alignment and grade. Space should also be provided for the filling around the pipe to be properly placed. Where an artificial foundation is necessary the trench must be wide and deep enough to receive it. The excavation should be at least six inches wider than the outside diameter of the pipe to comply with the above requirements.

Trenches must frequently be excavated in materials, wholly or partly saturated, in which banks will not stand vertically or even on steep slopes without being supported. Not infrequently tight sheeting and heavy bracing is necessary to hold a trench open. Where such conditions prevail there is sometimes a choice between excavating a narrow trench which will require sheeting and bracing, and one with sloping banks that will require little or no protection to keep it open. The narrow trench requires but a small amount of excavation but, on account of extra work and material required to keep it open, its cost may equal or exceed that of a wide one where little or no protection work is needed.

Excavation for closed drains, generally can be most economically accomplished by machinery. Hand work may sometimes be practical for small shallow drains, or in soils over which a machine cannot be worked. Various kinds of trenching machines are manufactured for cutting trenches with vertical sides and with dimensions up to about four feet wide and twenty feet deep. These machines differ greatly as to details but are similar in the general principles of their construction. They are operated

FIG. A.—Excavating for tile drain with trenching machine. The upper portion of banks are sloped to prevent caving.

FIG. B.—Constructing tile drain in unstable material. Solid sheating required to keep trench open.

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Fig. C.—Interior of trench for tile drain showing bracing used to support trench walls.

Fig. D.—Back filling machine completing closed drain. Shoshone Project, Wyoming.

by steam or gasoline power and equipped with a mechanism by means of which the machine is moved at the required rate of speed and a digging apparatus which may be operated independent of the movement of the machine. The digging apparatus consists generally of a train of buckets, provided with cutting edges, and carried on an endless chain or revolving wheel. This loosens the material, carries it out of the trench and deposits it onto a moving web which transports it laterally and deposits it along the side of the excavation. In soft saturated material it is necessary to place sheeting and supports immediately behind the machine to prevent banks caving and partly refilling the trench.

Trenching machines are sometimes equipped with a metal shield or cage which is drawn through the trench behind the machine to prevent banks caving. The tile layer works in this shield and places the pipe immediately behind the excavation. As the shield moves forward the banks behind it are left free to cave over the pipe already in place.

The use of a shield in the above manner does not permit the placing of an artificial foundation under the pipe, nor of properly surrounding it with porous materials. Another objection to its use is the danger of tile being drawn forward by the movement of the shield, thus leaving open joints in the line.

Where a trench with sloping banks is used, the work of excavation does not differ materially from open drain construction, except that it is unnecessary to make the section uniform and banks may be as steep as they will stand for the short period until tile is placed. A drag line excavator is well adapted to work of this kind. It may be operated along the center line of the drain and an excavation made which will be but little wider than the bucket provided banks will stand. Where sloughing occurs no more material need be removed than is necessary to reach the required depth.

Backfilling Trenches.—Before the work of backfilling trenches is started, tile should be covered to a sufficient depth to hold it in place and give protection. This covering, which is essentially hand work, should be done with sufficient care to insure the tile being thoroughly bedded and given lateral support. The filling on the sides of the pipe should be firmly compacted in order to increase the resistance which the pipe offers against crushing, and also to provide partial support for the load of backfill which

must be carried. The depth of hand covering required will vary for different sizes of pipe and character of material but generally it should be not less than 12 inches.

Backfilling after pipe is covered may be done by means of teams and scrapers or by machinery. Whatever method is used, it is necessary to protect pipe from being broken by heavy loads such as the weight of a machine, or the dropping of large masses of earth, on the soft fill directly above it. Backfilling machines which are especially intended for small trenches are of standard manufacture and easily obtainable. A portable drag-line is well suited for backfilling where large quantities of material must be handled.

Loads on Pipes.—The load which a tile must sustain is difficult to determine accurately on account of the many uncertain factors upon which it depends. For the same height of fill the load may vary for different soil conditions, width of trench, and manner in which the fill has been placed.

The weight of the backfill may be supported partly by the pipe, partly by the bottom of the trench along the side of the pipe and partly by friction between the fill and sides of the trench. The support offered by each of the last two may be small, or even negligible, under some conditions and the load on the pipe consequently increased. Attention has already been called to necessity of material, on the sides of pipe, being firmly compacted, in order that it may carry a portion of the load of backfill above. It is possible, but not always practical, to make this fill as firm as the bottom of the trench so that it will carry its portion of the load without any greater tendency to settle than the pipe itself.

The factors which affect in a marked degree the load on pipes, are the weight per unit volume, or density of fill, the internal friction of the fill and the friction between the fill and sides of the trench. Each of these are subject to variations due to character of materials and degree of saturation. The weight of earth varies generally from about 70 to 160 pounds per cubic foot. The lower limit is for loose soils dry or but slightly moist; the upper limit is for dense material, thoroughly compacted and saturated. The internal friction of the fill and also that between it and the side walls of the trench may be high when the material is dry but very low when it is wet. Saturation of the fill consequently may greatly increase the load on pipes. This increase is more pronounced when the fill first becomes saturated than after it has

FIG. A.—Back filling closed drain with drag line excavator.

FIG. B.—Back filling closed drain with teams and road grader.

(*Facing Page* 140)

become settled and compacted. The greatest loading on pipes may consequently not occur for some time after they are put in place.

The question of loads on pipes has been investigated theoretically by Marston and Anderson[1] and the results obtained checked by weighings to within a reasonably close degree of agreement. In the investigations it was assumed that all the weight of fill is carried by the pipe and friction with the sides of the trench, no allowance being made for support of the filling on the sides of the pipe. From this it is deducted that, up to certain limits, the load on the pipe increases with the width of the trench. It is stated, however, that for an extremely wide ditch this principle would no longer hold sufficiently correct. It also follows, from the above, that for the same trench width and other similar conditions the load on a small pipe will be the same as on a large one.

In checking the results by actual weighings of loads on pipes the apparatus was so arranged that no support was gotten from filling on the sides of the pipe, which was in agreement with premises assumed for theoretical investigations. The results may be somewhat in excess of those to be obtained in practice since the conditions upon which they are based are the most severe that can be imposed. This is especially the case when trenches are excavated very much wider than the outside diameter of the pipe, and when care is taken to make the side filling of firm material thoroughly compacted.

The mathematical notation used by Messrs. Marston and Anderson is as follows:

W = total weight on pipe per unit of length.
V = the average intensity of vertical pressure at the top of pipe, per unit of area.
w = the weight of ditch filling per unit of volume.
B = the breadth of ditch a little below the top of pipe.
H = height of ditch filling, above top of pipe.
μ = the coefficient of internal friction.
K = the ratio of lateral to vertical earth pressure.
μ' = the coefficient of friction of ditch filling against the side of the ditch.

[1] The Theory of Loads on Pipes in Ditches by A. Marston and A. O. Anderson, Iowa State College of Agriculture and Mechanical Arts, *Bulletin* No. 31, Engineering Experiment Station.

ϵ = the base of Naperian logarithms.

C = a coefficient of loads on pipes in ditches. C = the average vertical pressure per unit area in a ditch of unit width under a ditch filling material weighing unity per unit volume.

NOTE 1.—Corresponding units must be used throughout for all the above quantities. It is best to state all quantities in feet and pounds.

NOTE 2.—K may be calculated by Rankine's formula.

$$K = \frac{\sqrt{\mu^2 + 1} - \mu}{\sqrt{\mu^2 + 1} + \mu}$$

The mathematical expression developed for W is

$$W = \frac{1 - \dfrac{1}{\epsilon^{2K\mu'\frac{H}{B}}}}{2\,K\mu'}\,wB^2$$

This may be written in the form.

$$W = CwB^2$$

in which

$$C = \frac{1 - \dfrac{1}{\epsilon^{2K\mu'\frac{H}{B}}}}{2K\mu'}.$$

In this expression μ should be used instead of μ' whenever μ' is greater than μ.

For actual calculations of loads on pipes in ditches the values of C may be taken from the following table.

TABLE 7.—APPROXIMATE SAFE WORKING VALUES OF "C," THE COEFFICIENT OF LOADS ON PIPES IN DITCHES

Ratio $\frac{H}{B}$	Approximate value of "C"			
	For damp top soil and dry and wet sand	For saturated top soil	For damp yellow clay	For saturated yellow clay
0.5	0.46	0.47	0.47	0.48
1.0	0.85	0.86	0.88	0.90
1.5	1.18	1.21	1.25	1.27
2.0	1.47	1.51	1.56	1.62
2.5	1.70	1.77	1.83	1.91
3.0	1.90	1.99	2.08	2.19
3.5	2.08	2.18	2.28	2.43
4.0	2.22	2.35	2.47	2.65
4.5	2.34	2.49	2.63	2.85
5.0	2.45	2.61	2.78	3.02
5.5	2.54	2.72	2.90	3.18
6.0	2.61	2.81	3.01	3.32
6.5	2.68	2.89	3.11	3.44
7.0	2.73	2.95	3.19	3.55
7.5	2.78	3.01	3.27	3.65
8.0	2.82	3.06	3.33	3.74
8.5	2.85	3.10	3.39	3.82
9.0	2.88	3.14	3.44	3.89
9.5	2.90	3.18	3.48	3.96
10.0	2.92	3.20	3.52	4.01
11.0	2.95	3.25	3.58	4.11
12.0	2.97	3.28	3.63	4.19
13.0	2.99	3.31	3.67	4.25
14.0	3.00	3.33	3.70	4.30
15.0	3.01	3.34	3.72	4.34
Infinity	3.03	3.38	3.79	4.50

From the values of C given in the above table, the width of trench B, and the value of w, which must be gotten by experiment, the loads on pipes may be computed by substituting in formula $W = CwB^2$. The results of such computations for different weights of materials and widths of trench are given in the following table.

TABLE 8.—APPROXIMATE ORDINARY MAXIMUM LOADS ON DRAIN TILE AND SEWER PIPE IN DITCHES FROM COMMON DITCH FILLING MATERIALS IN POUNDS PER LINEAR FT.

H = Height of fill above top of pipe	B = Breadth of ditch, at top of pipe									
	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.
	Partly compacted damp top soil 90 lbs. per cu. ft.					Saturated top soil 110 lbs. per cu. ft.				
2 feet	130	310	490	670	830	170	380	600	820	1020
4 feet	200	530	880	1230	1580	260	670	1090	1510	1950
6 feet	230	690	1190	1700	2230	310	870	1500	2140	2780
8 feet	250	800	1430	2120	2790	340	1030	1830	2660	3510
10 feet	260	880	1640	2450	3290	350	1150	2100	3120	4150
	Dry sand 100 lbs. per cu. ft.					Saturated sand 120 lbs. per cu. ft.				
2 feet	150	340	550	740	930	180	410	650	890	1110
4 feet	220	590	970	1360	1750	270	710	1170	1640	2100
6 feet	260	760	1320	1890	2480	310	910	1590	2270	2970
8 feet	280	890	1590	2350	3100	340	1070	1910	2820	3720
10 feet	290	980	1820	2720	3650	350	1180	2180	3260	4380
12 feet	300	1040	2000	3050	4150	360	1250	2400	3650	4980
14 feet	300	1090	2140	3320	4580	360	1310	2570	3990	5490
16 feet	300	1130	2260	3550	4950	360	1350	2710	4260	5940
18 feet	300	1150	2350	3740	5280	360	1380	2820	4490	6330
20 feet	300	1170	2420	3920	5550	360	1400	2910	4700	6660
22 feet	300	1180	2480	4060	5800	360	1420	2980	4880	6960
24 feet	300	1190	2540	4180	6030	360	1430	3050	5010	7230
26 feet	300	1200	2570	4290	6210	360	1440	3090	5150	7460
28 feet	300	1200	2600	4370	6390	360	1440	3120	5240	7670
30 feet	300	1200	2630	4450	6530	360	1440	3150	5340	7830
Infinity	300	1210	2730	4850	7580	360	1450	3270	5820	9090
	Partly compacted damp yellow clay 100 lbs. per cu. ft.					Saturated yellow clay 130 lbs. per cu. ft.				
2 feet	160	350	550	750	930	210	470	730	1000	1240
4 feet	250	620	1010	1400	1800	340	840	1330	1870	2370
6 feet	300	830	1400	1990	2580	430	1140	1900	2630	3410
8 feet	330	990	1720	2500	3250	490	1380	2360	3360	4400
10 feet	350	1110	2000	2920	3880	520	1570	2760	3980	5270
12 feet	360	1200	2220	3320	4450	540	1730	3100	4560	6050
14 feet	370	1280	2410	3650	4950	560	1850	3410	5050	6760

TABLE 8.—(*Continued*)

H = Height of fill above top of pipe	B = Breadth of ditch, at top of pipe									
	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.
	Partly compacted damp yellow clay 100 lbs. per cu. ft.					Saturated yellow clay 130 lbs. per cu. ft.				
16 feet	370	1330	2570	3950	5400	570	1940	3660	5510	7440
18 feet	380	1380	2710	4210	5810	570	2020	3880	5930	8060
20 feet	380	1410	2830	4450	6180	580	2090	4070	6280	8610
22 feet	380	1430	2920	4640	6500	580	2140	4240	6610	9130
24 feet	380	1450	3000	4820	6800	580	2180	4380	6910	9590
26 feet	380	1470	3060	4980	7080	580	2210	4500	7160	10010
28 feet	380	1480	3120	5100	7310	580	2240	4610	7380	10430
30 feet	380	1490	3170	5230	7530	580	2260	4700	7590	10780
Infinity	380	1520	3410	6060	9480	580	2340	5270	9360	14620

Table 8 is intended by the authors to furnish sufficient data on probable maximum loads, on pipes in ditches to allow safe strengths of pipe to be determined.

The above formula and tables hold also for ditches with sloping banks, the width of trench in this case to be taken at about the upper 45° line or just below the top of the pipe.

Physical Properties of Drain Tile.—The essential properties of drain tile are durability and strength. They must resist decay and disintegration and be strong enough to support the load of backfill without crushing. Durability depends upon the material of which the pipe is composed. Agencies which may cause disintegration are freezing and chemical constituents found in the soil. Freezing causes the expansion of water contained in the pores of the pipe with sufficient pressure to cause a breaking of the surface particles. Chemical disintegration is due to the action of certain alkali salts which are carried in solution Disintegration may also be caused by the evaporation of waters carrying mineral salts in solution; the salts which are left in the surface pores expand upon crystallization and have much the same effect on the pipe as water in freezing. This action can take place only when the pipe is partly exposed to the drying action of the atmosphere, a condition not generally found in closed drains. The effect of freezing is also absent when pipes are below the frost zone.

Disintegration such as described above can take place only in porous material; if no water is absorbed by the pipe it cannot

be affected, or at least but slightly, by any of the agencies mentioned. It is impractical, if not impossible, to make a pipe which will not absorb water, from materials such as clay or cement. Greater durability, however, is obtained by reducing the amount that will be absorbed to a minimum. This is especially true of a material that is disintegrated by salts in solution in soil waters. Attention has already been called to the disintegrating action of some alkalis on cement. It is well known that a dense concrete will withstand this action better than a porous one. A dense pipe, generally, has the greater strength also.

The strength of clay pipe depends largely upon the character of clay, the methods used in its manufacture, and up to certain limits, upon the temperature to which it is subjected in burning. To make a strong dense pipe, it must be burned until vitrified. The clay must be of such quality, and it must be so moulded in the pipe shell that it will stand the required temperature without a serious distortion of its shape.

The property of material which determines the strength of a pipe for supporting a vertical load is its tensile strength. If the diameter of the pipe, thickness of shell and tensile strength of the material be known the resistance of the pipe to crushing may be computed.

The equations derived by Talbot[1] for vertical loads are

$$\frac{Pt^2}{6} = .159\frac{dw}{12} \tag{1}$$

for a load concentrated along the crown of the pipe and

$$\frac{Pt^2}{6} = .0625\frac{dw}{12} \tag{2}$$

for a load uniformly distributed over the top 180 degrees of the pipe. In the above

P = unit stress in the remotest fiber
t = thickness of the tile shell
d = diameter of the center line of pipe shell
w = the total load in pounds per lineal foot of tile.

For a load uniformly distributed over the top 90 degrees of the tile the equation is

$$\frac{Pt^2}{6} = .0845\frac{dw}{12} \tag{3}$$

[1] University of Illinois Engineering Experiment Station *Bulletin* No. 22.

From the above it will be seen that the manner of its distribution has a marked influence on the load which a pipe will support. It is difficult to determine what constant to apply to the right side of this equation to satisfy the distribution of the load for a partiular case in actual practice.

The load which a pipe will support when applied through a sand bearing over 90 degrees of the top of the pipe has been defined as its ordinary supporting strength. The equation for this, as determined by experiment, is

$$\frac{Pt^2}{6} = .10\frac{dw}{12} \tag{4}$$

The method of computing the strength of pipe is of interest theoretically and also serves to determine roughly the thickness of shell required to meet certain requirements. It is not practical for determining the actual loads that pipe will stand on account of the difficulties in obtaining an accurate value of the tensile strength of the material of which the pipe is composed. The practical method for testing the strength of a pipe is to measure the load necessary to crush it. This, when applied to a number of samples, gives a result which may fairly represent the average strength of the lot from which samples are taken. Careful inspection is then necessary to exclude defective tile whose strength may be less than the minimum allowed.

The strength of pipe, as has already been stated, depends not alone upon the material of which it is composed but also upon the method of manufacture. This includes the grinding, moulding, drying and burning of clay pipe and the grading and mixing of aggregates and methods of moulding and curing for concrete pipe. The effect of burning upon clay pipe is clearly shown by the difference in strengths of pipe, otherwise similar, but burned at different temperatures due to their positions in the kiln. On acoount of these variations, it is necessary that tests be made of samples taken from each different lot of pipe.

The principal points that should be covered in an inspection are size, shape and the presence of defects which may decrease the strength or otherwise render the pipe unfit for use. One of the important points in connection with the inspection of clay pipe is to detect cracks that have been developed either in the process of cooling, or by improper handling after the pipe is burned. Such cracks may be small and extend so short a distance

into the pipe shell that its strength is not materially decreased by them. There is always the danger, however, that a crack once started, may increase in size and finally cause a weakening that will result in failure.

In testing bearing strengths, different methods are used for applying the load. The most common of these are Sand Bearings, Hydraulic Bearings, Three Point Bearing, Fig. 30. With the sand bearings the bottom of pipe is bedded to a width of 90

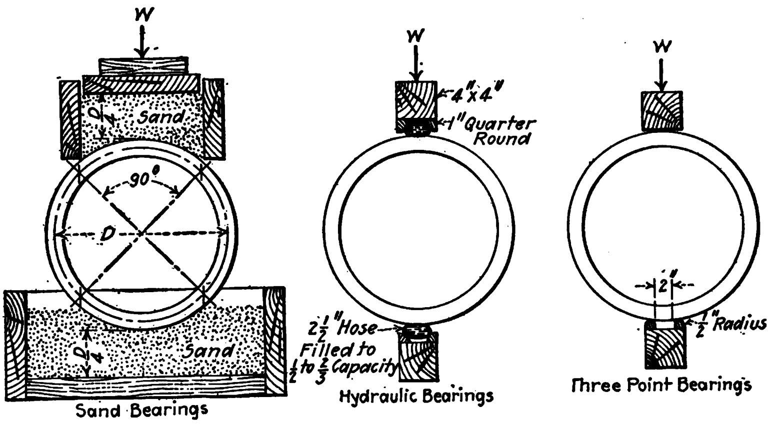

FIG. 30.—Bearings used in making tests of crushing strengths of tile.

degrees of the circumference of the center line of shell and the load applied through a similar sand cushion on the top. None of the timbers or boxes containing the sand are allowed to touch the pipe. With Hydraulic Bearings the pipe is supported on and the load applied through a two and one-half inch hose laid lengthwise of the pipe and partly filled with water. With the Three Point Bearing, the pipe is supported along two lines spaced two inches apart and the load applied along a single line at the crown. With either form of bearing the load may be produced by means of a testing machine or any other form of apparatus that will give the required pressure. A platform may be constructed on the top of the bearing and sufficient weight piled upon it to break the pipe. For the latter method of loading the sand bearing is most convenient on account of the greater stability offered by it.

Test made by means of sand bearings give, directly, the ordinary supporting strength of the pipe. It is customary in reporting results of tests by means of other bearings to give them in the same form. Those gotten by means of hydraulic bearings

may be reduced to ordinary supporting strengths by multiplying them by 1.25 and those from three point bearings by 1.50. The value of the latter factor which has been gotten largely from experimental data is slightly less than the theoretical value given by equations 1 and 4.

In preparing specifications for tile, the principal points to be covered, as heretofore mentioned, are character of material, strength, size, shape and soundness. In some cases limits on the thickness of shell is also included. This, however, is of

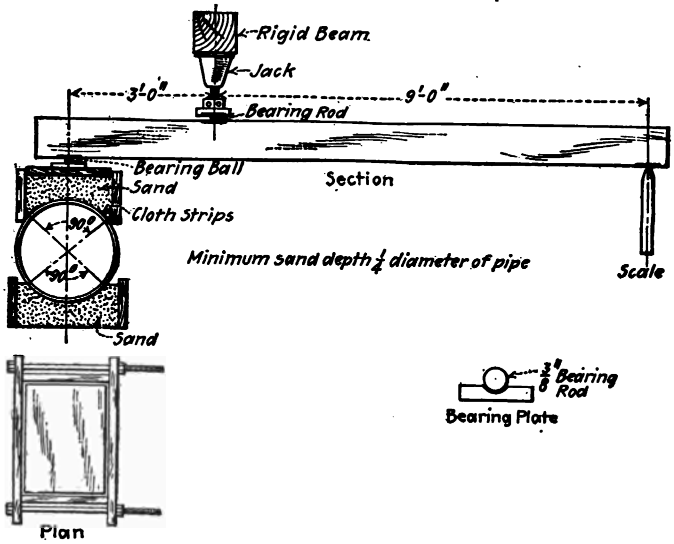

FIG. 31.—A simple form of testing machine for determining strength of pipe.

doubtful value on account of the varying thicknesses required with different materials for the same strength of pipe. Specifications for double or single strength pipe are without definite meaning and should be avoided. These terms refer to the thickness of shell only, and what is termed double strength pipe of one material may offer far less resistance to crushing than single strength from another. The limits of deviation from true size and shape should be made to suit particular requirements and may be varied for different classes of work and conditions.

The following specifications for clay tile are those used by the U. S. Reclamation Service. They are intended to cover the requirements for pipe for drains ranging, generally, from eight to eleven feet deep constructed in various soils found in the irrigated areas.

Specifications for Tile

1. Each tile shall be of cylindrical section, the size being designated by the interior diameter. The average diameter shall not be more than 3 per cent. less than the specified diameter. The maximum and minimum diameters of the same tile and the average diameters of tiles intended to be used adjacent to each other, shall not differ more than 80 per cent. of the thickness of the wall. Tile shall be two feet in length. Tile designated to be straight; shall not deviate materially from a straight line, and the ends shall be practically at right angles to the center line. Tile shall be reasonably smooth on the inside and free from cracks and checks, extending into the body of the tile in such a manner as to appreciably decrease the strength. Tile stood on end and tapped with a light hammer, when dry, shall give a clear ring. Tile shall be free from chips and broken pieces that will decrease its strength or admit earth into the drain. The ends shall be regular and smooth and admit of the making of a close joint when properly turned and pressed together.

2. Tile shall be partially salt-glazed, and be burnt to sufficient temperature to vitrify the material and produce strong dense walls.

3. Tile shall be delivered f.o.b. cars at the works of the bidder, ready for shipment, and the bidder shall state in the proposal the point at which he proposes to make delivery. Shipments will be made on Government bills of lading, furnished by the United States. The bidder will state in the blanks provided therefore, the time after acceptance of the proposal, that deliveries will be begun and completed. In estimating the amount of freight charges from point of delivery to destination, the following weights for various sizes of pipe will be used:

6″ pipe	11 lb. per foot
8″ pipe	18 lb. per foot
10″ pipe	26 lb. per foot
12″ pipe	35 lb. per foot
15″ pipe	55 lb. per foot
18″ pipe	75 lb. per foot
20″ pipe	95 lb. per foot

4. Tile shall have minimum average supporting strengths when tested by the method herein described, not less than the following:

6″ pipe	1000 lb. per lin. foot
8″ pipe	1200 lb. per lin. foot
10″ pipe	1500 lb. per lin. foot
12″ pipe	1800 lb. per lin. foot
15″ pipe	2000 lb. per lin. foot
18″ pipe	2300 lb. per lin. foot
20″ pipe	2600 lb. per lin. foot

5. Tile will be inspected and tested at the point of delivery. The contractor shall furnish the necessary tile for tests, free of charge, provided, however, that in case the specimens tested meet the specifications for strength, not more than one-half of 1 per cent. of the tile being supplied, will be furnished free.

6. Specimens to be tested shall be selected by the Inspector from the tile furnished. They shall be unbroken, full size tile, and be weighed, when practicable, just prior to the test. Five specimens from each materially different class of tile shall be selected for a standard test to determine the minimum average supporting strength. In a standard test, if one or more specimens fall more than 5 per cent. below the strength, as specified, the class of tile represented by the failing specimens shall be rejected.

7. In making strength tests, the sand-bearing method will be used. Specimens shall be accurately marked in quarters with pencil or crayon, prior to the test. Specimens shall then be carefully bedded, above and below in sand, for one-fourth the circumference, of the pipe, measured on the middle line of the pipe shell. The depth of bedding above and below the pipe at thinnest points shall, at each place, be equal to one-fourth the diameter of the pipe, measured between the middle lines of the pipe walls. The sand used shall be clean sand, which shall pass a No. 4 screen.

8. The frames of the top and bottom bearings shall be composed of timbers sufficiently heavy to prevent bending by the side pressure of the sand. The frames shall be dressed on their interior surfaces. No frames shall come in contact with the pipe during the test. A strip of cloth may be used inside the upper frame to prevent the escape of sand between the frame and the tile.

SPECIFICATIONS FOR TILE DRAINS

It is impractical to attempt to give a specification which will cover all of the conditions that may be met in practice. The character of material in which tile are laid and the kind of artificial foundation, if any, that may be required must be carefully considered in each particular case and plans and specifications made to suit conditions. Whether or not material excavated from the trench is suitable for filling around pipe is an important factor and can be determined only by careful examination.

The following specifications are intended to cover general requirements and to serve in many cases as a complete guide for construction work. They should be modified where necessary to cover particular conditions.

Earth Work

1. Trench Sections and Grades.—Trenches shall be excavated to sufficient bottom width to receive the size tile designated therefor. For 18-inch tile, the bottom width shall be not less than 24 inches; for 15-inch tile, not less than 21 inches; and for 12-inch tile not less than 18 inches.

The side slopes shall be made as steep as the banks will stand, or as is practicable by the method used for taking out the excavation.

Excavation shall be made accurately to the grades shown on the drawings or as staked out by the Engineer. Excavation for trap boxes shall be made at the point designated, which will be approximately 1000 feet apart. The excavations for these boxes shall be approximately four feet square and carried down one foot below the grade of trenches.

2. Backfilling Trenches.—Immediately after the tile has been placed, trenches shall be filled by hand to a depth of not less than 12 inches over the top of the pipe. The remainder of the back-filling may be done by means of a grader, backfilling machine, or by teams and scrapers, in a manner satisfactory to, and approved by the engineer. In back-filling, the first six inches over the tile, the coarsest and most porous material taken from the excavation shall be used. This material shall be carefully placed and sufficiently tamped to form a supporting cradle for holding the tile to grade and alignment and also to form a partial support at the side of the pipe for the load of backfill. Where material taken from the excavation is not suitable for bedding, and covering tile, gravel or other porous material satisfactory to the engineer shall be provided. Where gravel is found in the excavation, it shall be used for covering the tile, but stones exceeding two inches in diameter shall be placed immediately over the top of the pipe.

3. Surface Water.—Where it is necessary to cross irrigation canals or surface drainage ditches, such ditches shall be diverted and care shall be taken to see that surface water is not turned into the drain.

Irrigation canals or drainage ditches constructed across tile lines shall have the bottoms and banks carefully compacted so as to avoid to the greatest degree possible seepage from these canals or ditches into the tile line below.

Laying Tile

4. Grade and Alignment.—Tiling shall be laid true to grade and alignment. The foundation upon which they are placed shall be sufficient to prevent settlement. Where trenches are excavated in material too soft to support the tile, a foundation of wood or other suitable material shall be used.

Where trenches have been excavated below grade they shall be refilled to grade and the material so replaced carefully compacted by tamping or

other suitable means. The person directly in charge of tile laying shall check the accuracy of the grades at every station where the cut is given and at sufficient intermediate points to insure uniformity of slope. The variation from the true grade at any point shall not exceed 10 per cent. of the inside diameter of the tile and in no case shall it be more than one inch.

Reference hubs, from which to determine the depth of the cut, will be set at intervals of not greater than 50 feet, and oftener when necessary.

5. Joints.—The ends of tile shall be laid in contact in such a manner as to make as tight joints as possible after the tiles are in place. The top of each joint shall be covered by a strip of tar paper or burlap saturated with asphaltum. Such strips shall be not less than three inches in width and approximately ⅔ of the outside circumference of the tile in length.

6. Time of Laying Tile.—It is advisable that the work of laying tile follow as closely as practicable the work of excavation. Where, however, the banks are firm and there is no tendency for them to cave, excavation should be kept fifty feet or more ahead of the tile laying in order that the grades may be more readily checked. The work of excavation should in no case be delayed on account of the tile laying, unless the material is such that trenches cannot be kept open.

7. Trap Boxe .—Trap boxes shall be constructed at intervals of approximately 1000 feet and in every case where there is a change in grade or alignment. These trap boxes shall be not less than 3 × 4 feet in size and may be made up of two-inch planking spiked to 4 × 4 inch corner pieces. They shall extend not less than one foot below the bottom of the tile and be provided with a suitable floor to prevent the bottom rising in them. Trap boxes shall be provided with suitable covers so they may be closed and locked.

8. Protection of Outlet.—The outlet of each line shall be protected by means of a box or bulkhead of wood or concrete. A trap box with the bottom portion of the lower side left open may be used.

Results of Breaking Tests.—The following tabulations give the ordinary breaking strengths and dimensions of a number of representative samples of well-vitrified clay tile. The four lots of samples, Table 9, are the products of different manufacturers and the material from which they were made were taken from localities widely separated from each other. It is to be noted that there are considerable variations both in the strengths and thickness of shells but that no definite relationship exists between them.

TABLE 9.—ORDINARY SUPPORTING STRENGTHS OF CLAY TILE

(Lot 1)

	No.	Weight, pounds	Length, inches	Thickness, inches	Breaking load, lb.	Breaking load, lb. per lin. ft.
10-in. tile	1	49	24	3/4	3470	1735
	2	50	24	3/4	3750	1875
	3	50	24	3/4	3820	1910
	4	49	24	3/4	3974	1987
	5	49	24	3/4	4464	2232
Ave.						1948
12-in. tile	1	66	24	7/8	4242	2121
	2	67	24	7/8	4095	2047
	3	67	24	7/8	4347	2173
	4	67	24	7/8	4312	2156
	5	67	24	7/8	3850	1925
Ave.						2084
15-in. tile	1	98	24	1	4185	2092
	2	98	24	1	4591	2295
	3	100	24	1	4010	2005
	4	99	24	1	4115	2057
	5	99	24	1	4080	2040
Ave.						2098
18-in. tile	1	129	23 3/4	1 1/16	5685	2871
	2	130	24	1 1/16	4754	2377
	3	133	24	1 1/8	5020	2510
	4	128	24	1 1/16	5618	2809
	5	127	23 1/2	1 1/16	6245	3188
Ave.						2751

TABLE 9.—(*Continued*).

Lot 2

	No.	Weight, pounds	Length, inches	Thickness, inches	Breaking load, lb.	Breaking load, lb. per lin. ft.
10-in. tile	1	60	24	$^{15}/_{16}$	3530	1765
	2	60	24	$^{15}/_{16}$	3614	1807
	3	60	24	$^{15}/_{16}$	3518	1759
	4	59	24	$^{15}/_{16}$	3330	1665
	5	60	24	$^{15}/_{16}$	3370	1685
Ave.						1736
12-in. tile	1	82	24	$1^{1}/_{32}$	4505	2252
	2	80	24	$1^{1}/_{32}$	4065	2032
	3	81	24	$1^{1}/_{32}$	3745	1872
	4	82	24	$1^{1}/_{32}$	3865	1932
	5	83	24	$1^{1}/_{32}$	4045	2022
Ave						2022
15-in. tile	1	115	24	$1^{3}/_{16}$	4136	2068
	2	112	24	$1^{3}/_{16}$	4176	2088
	3	113	24	$1^{3}/_{16}$	4236	2118
	4	112	24	$1^{3}/_{16}$	4008	2004
	5	112	24	$1^{3}/_{16}$	4296	2148
Ave.						2085
18-in. tile	1	179	24	$1^{1}/_{2}$	5040	2520
	2	180	24	$1^{1}/_{2}$	5340	2670
	3	183	24	$1^{1}/_{2}$	5988	2994
	4	181	24	$1^{9}/_{16}$	5580	2790
	5	180	24	$1^{9}/_{16}$	5796	2898
Ave.						2774

TABLE 9.—(*Continued*).

Lot 3

	No.	Weight, pounds	Length, inches	Thickness, inches	Breaking load, lb.	Breaking load, lb. per lin. ft.
10-in. tile	1	50	24	7/8	4430	2215
	2	49	23 3/4	7/8	3410	1722
	3	52	24	7/8	3688	1844
	4	52	24	7/8	4250	2125
	5	50	23 3/4	7/8	5592	2824
Ave.						2146
12-in. tile	1	71	24	1	4880	2440
	2	70	24	1	5054	2527
	3	67	24	15/16	4640	2320
	4	68	24	15/16	4638	2319
	5	68	24	1	4944	2472
Ave.						2114

Lot 4

	No.	Weight, pounds	Length, inches	Thickness, inches	Breaking load, lb.	Breaking load, lb. per lin. ft.
15-in. tile	1	131	30	1 1/8	4804	1922
	2	132	30	1 1/8	5714	2286
	3	129	29 1/4	1 1/8	5159	2117
	4	132	30	1 1/8	5064	2026
	5	131	30	1 1/8	5064	2026
Ave.						2075
18-in. tile	1	187	30	1 1/4	5505	2202
	2	185	30	1 1/4	6475	2590
	3	185	30	1 1/4	6425	2570
	4	185	30	1 1/4	5185	2074
	5	186	30	1 1/4	6890	2756
Ave.						2438

Table 10 shows results of breaking tests and the per cent. of absorption for a number of samples of pipe of the same character as those of Lot 1, Table 9, except a few which were not thoroughly vitrified. For convenience they have been arranged in the order of supporting strengths for the different sizes and thicknesses of shell. The results show, generally, that strength increases as porosity decreases, but the relation between them is not such that it can be expressed mathematically.

TABLE 10

	No.	Weight, pounds	Length, inches	Thickness, inches	Breaking load, lb. per ft.	Per cent. of absorption
8-in. tile	1	39	24	¾	1415	7.6
	2	39	24	¾	1564	7.0
	3	39	24	¾	1784	5.1
	4	39	24	¾	1800	5.0
	5	40	24	¾	1905	4.7
	6	39	24	¾	2233	1.3
	7	40	24	¾	2267	2.5
	8	39	24	¾	2285	2.5
10-in. tile	1	49	24	¾	1613	4.8
	2	50	24	¾	1624	3.2
	3	50	24	¾	1635	3.7
	4	50	24	¾	1647	2.2
	5	49	24	¾	1681	3.3
	6	51	24	¾	1702	2.7
	7	51	24	¾	1830	2.7
	8	50	24	¾	1840	3.0
	9	49	24	¾	1845	3.0
	10	51	24	¾	1940	1.5
	11	50	24	¾	1965	1.5
	12	50	24	¾	2042	1.5
12-in. tile	1	62	24	¾	1162	6.4
	2	61	24	¾	1282	4.7
	3	62	24	¾	1552	3.6
	4	62	24	¾	1891	2.4
	5	63	24	¾	1964	2.4
	6	56	24	¾	2011	2.2
	7	61	24	¾	2140	2.2
	8	61	24	¾	2244	2.0
	9	62	24	¾	2440	1.0
12-in. tile	1	59	24	1³⁄₁₆	1155	7.2
	2	63	24	1³⁄₁₆	1389	6.4
	3	62	24	1³⁄₁₆	1591	2.8
	4	62	24	1³⁄₁₆	1611	3.6
	5	62	24	1³⁄₁₆	1676	2.8
	6	62	24	1³⁄₁₆	1802	2.8
	7	63	24	1³⁄₁₆	2044	2.8
	8	62	24	1³⁄₁₆	2264	1.8
15-in. tile	1	94	24	1⁵⁄₁₆	1901	2.6
	2	94	24	1⁵⁄₁₆	2263	1.3
	3	96	24	1⁵⁄₁₆	2362	1.6
	4	92	24	1⁵⁄₁₆	2427	1.4
	5	97	24	1⁵⁄₁₆	2588	1.2
	6	92	24	1⁵⁄₁₆	2869	0.8
	7	95	24	1⁵⁄₁₆	3366	0.7

Maintenance and Care of Drains.—Attention has been called to the necessity of maintaining drains to prevent their efficiency becoming impaired. There is a constant tendency for an open channel to become filled or obstructed and its depth decreased. The most common causes of such deterioration are silting, sloughing, or washing down of banks, and growth of vegetation. None of these can be entirely avoided, with open channels in earth; and constant maintenance is necessary to keep a drain in perfect working condition at all times. The amount of maintenance that will be required, however, may be reduced by frequent inspection, and proper care.

Silting and erosion are frequently the result of obstructions which cause the water to be held up over one section, and excessive velocity created over another. They may be prevented, in a large measure, by promptly removing obstructions that occur in the channel. Sloughing and washing of banks, into a drain, are often due to surface water being allowed to collect along, and flow over slopes. This condition may be avoided by providing suitable inlets through which water may enter the drain, and preventing it from entering except through them.

The growth of vegetation in an open drain canno be avoided in some soils and under some climatic conditions. Where this is the case the only remedy to prevent a drain becoming obstructed is frequent cleaning of the water-way.

Closed drains may become obstructed due to the breaking or displacement of a tile or the washing of material into the line. One common cause of trouble in a closed drain is surface water which finds its way directly to it. This causes a saturation of the fill, increases the load on pipes, and also tends to carry material into them. The latter may destroy the foundation or lateral supports and cause the pipe to be displaced or broken. A large inflow of surface water may cause the pipe to become overloaded and thus destroy or reduce its effect in drawing water out of the soil.

A closed drain, intended for the removal of ground water, should be protected from direct surface flow reaching it. Open channels, intended to carry excess surface water, and irrigation canals and laterals, should not be permitted near enough to closed drains to cause direct downward seepage into them. Where it is necessary to cross a closed drain, with an open waterway, the channel, of the latter, should be constructed of impervi-

FIG. A.—Outlet for tile drain with measuring wier, Carlsbad, N. M.

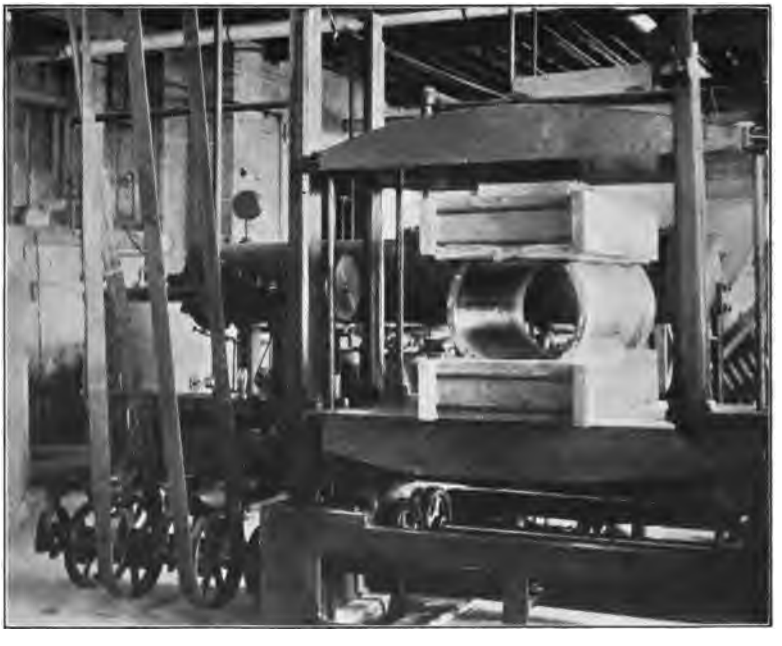

FIG. B.—Power testing machine used to determine crushing strength of pipe.

(*Facing Page* 158)

PLATE XII

FIG. C.—Cleaning and deepening open drain by means of drag line excavator, Yuma Project, Arizona.

FIG. D.—An open drain with water-way obstructed by vegetation.

ous material in such manner as to prevent water finding its way from it to the drain.

The proper maintenance of a drainage system requires that it be inspected at frequent intervals, and that any obstructions, which interfere with the proper action of a drain, be promptly removed. Where erosion occurs sufficient to threaten the banks or cause a filling of the water-way the channel should be protected against it. It is more economical to maintain a system in proper working condition, at all times, than to occasionally overhaul and put it in order; especially when its value for protecting land and crops is considered.

CHAPTER X

ECONOMIC CONSIDERATION OF DRAINAGE

Questions Involved.—In addition to the technical engineering work, a drainage enterprise involves questions of policy and economics that must be considered. These, in some cases, are not engineering questions but, in most instances, engineering data and conclusions are required to properly answer them.

The first and most important question is whether an enterprise should be undertaken. It may be possible, from a purely engineering standpoint, to drain and otherwise improve the soil of a wet and unproductive area and make it suitable for growing crops, yet the project, if undertaken, would be a failure from a practical and economic viewpoint. In any drainage enterprise the building of engineering works is only one step in carrying out what is necessary for its final development. It is necessary also to subdue the lands and to bring them to a state of productiveness. Conditions must be such that this can be accomplished in a practical and economic manner. It is necessary to take into account any adverse conditions which may tend to retard or prevent development. An idea must also be formed of how the drained lands can be used; what they can be made to produce, and the probable worth of such production, as a basis for estimating the real value of the proposed improvements.

None of the questions involved in a drainage project can be answered with absolute accuracy on account of the many uncertain factors which they involve. For this reason a project should be studied from various viewpoints before it is finally decided that it is feasible for construction.

Factors Which Govern Feasibility.—It is impossible to enumerate all of the various factors which will govern the feasibility of a particular project and which should be considered before it can be safely adopted. They may vary for each location, and be dependent in a large degree, upon local conditions. They include engineering possibilities, soils, climate, accessibility to markets, and transportation facilities. There are also questions

purely human in character that may have a marked influence on the development of a given section or locality. It should be remembered in practically all enterprises, that the human element is an important one and must be considered.

The engineering features and estimate of cost of improvements that are required, generally, should be worked out in considerable detail before a final consideration of the feasibility of a project can be taken up. After the engineering data are completed, the other factors mentioned above may be used in connection with them for a comprehensive study of the entire plan. It is assumed, of course, that preliminary examinations of all the different phases of a project have shown it to be worthy of investigation before detailed engineering studies are undertaken. Technical engineering skill is necessary to determine the possibilities, to provide plans and estimates of cost, and to construct the works necessary for making developments. It requires the coöperative efforts of many different people, however, to carry through a project to final success after the engineering works have been completed. When an area has been drained and made suitable for cultivation or other purposes, it must be cultivated or in some way made to pay returns on the value of the land, and cost of its improvement. The possibility of doing this depends upon many things, not the least of which is whether conditions are such as will induce men to devote their time and means to making the necessary developments and improvements. The capitalist who supplies funds for building a drainage system, the farmer who invests money in land and devotes his time to its cultivation, each expect, and are entitled to fair returns for the capital and labor expended. If the enterprise will not yield these returns, it cannot be considered feasible.

Drainage of New Lands.—The term new lands here refers to those which on account of their wet condition have never been brought under cultivation. Such lands may include swamps which are permanently covered with water, and also areas that are dry enough, during a portion of the time, to furnish a small amount of pasture or similar crops, but not suitable for cultivation.

In considering areas of this kind special attention must be given to the character of the soils and the effects of removing water from them. It is sometimes assumed that all wet or swamp lands are fertile and that they will be valuable for growing crops as soon as drained. This assumption is not warranted; in many

instances the soils are of such character that they will not produce. Swamp lands generally are composed largely of vegetable matter which contains plant food and other valuable soil constituents. Some plants will grow in soils composed wholly, or nearly so, of vegetable matter. Peat soils which are of this class are very productive and for some crops produce large returns. They are not well suited for many of the ordinary staple crops.

Swamp lands sometimes consist of a relatively thin surface layer of nearly pure vegetable matter underlaid by a hard impervious stratum. In some instances they are composed of soft muck largely vegetable in origin to a depth of many feet. Either of these classes may have but little value when they are drained. In the first instance there remains, after the water is removed, only a thin layer of vegetable soil resting on top of an impervious hard pan which plant roots will not penetrate. In the second instance the subsidence of the top soils, when the water is drawn out of them, may make drainage impractical. It is of course feasible, in a case of this kind, by going deep enough, to finally affect drainage. The expense of doing this may be prohibitive. The ideal conditions for reclamation by drainage of swamp lands are represented by a soil composed of a mixture of disintegrated rock and vegetable matter, of sufficient thickness to give the required depth when drained and of sufficient stability to prevent undue settlement. It is only in rare cases that a perfect combination such as this is found and it is generally necessary to deal with soils not ideal in character. It is important, however, to distinguish between soil conditions which promise success under proper treatment and those which invite failure.

Wet and swamp lands, before they are drained and reclaimed are often wholly unproductive. Their value, based upon their earning power, is practically nothing and any price that can be placed upon them is largely, if not wholly, a speculative one. The real value of drainage and other reclamation work, in a case of this kind, is the amount which it adds to the value of the land. If this is based upon its increased power of production it is, in many cases, what the land is worth after it is reclaimed. The price at which swamp lands are usually held is not based upon the returns they will produce. It is based, more often, upon what they should be worth after they are made productive through drainage and other improvements less some fixed amount for this work.

The total expense for draining an unproductive area of wet lands, and bringing it to a profitable state of cultivation is easily underestimated, and requires careful consideration. The period after drainage works have been constructed, and before lands have been brought to a productive state, is one of constant outlay and no returns. During this period, interest charges on money already expended for construction, are generally accumulating and are a legitimate part of the cost of improvements. In addition to the time and money spent in clearing or otherwise preparing lands for cultivation, roads must be provided, and other public improvements, necessary to make the area habitable, must be made. The cost of these, generally, must be paid from the land and may be considered a part of the expense of its reclamation and improvement. In other words the total expenditures, from the time construction work is begun, until lands are brought to a producing status must be taken into account.

Drainage for Improvement and Protection.—This class of drainage applies to lands that are, or have been in cultivation, but that require drainage to maintain the soils in proper condition for producing crops. It includes works intended to remove excess precipitation, which occurs during portions of the year, those intended to increase water movement through the soils, to lower and control ground waters, and protect lands from becoming water-logged and alkaline. The latter is required especially on irrigated lands of the arid and semi-arid regions.

In the humid areas the requirement for drainage may be to quickly carry away flood waters, which occur during heavy storms and prevent inundation, or it may be to draw excess water out of the soils and thereby improve its physical condition. The latter work is sometimes designated as "farm drainage" or the "under drainage of farms." The value of drainage for carrying away flood waters and for improving soils also depends upon conditions affecting the particular area involved. It may mean the saving of an entire crop during wet years, or an increase in production varying from a few per cent. to 100 per cent. or more. It may mean the difference between profitable and unprofitable farming.

In the arid and semi-arid regions, where alkali is prevalent in the soils, and it is necessary to control the elevation of ground water to prevent its rise, drainage is necessary to maintain lands in a condition for cultivation. In this case it may be regarded

as a protection as well as an improvement. When lands have become unfit for cultivation through lack of drainage, it is then necessary for their reclamation as well as protection. The value of drainage for the reclamation of lands that have become unfit for use, or for protecting them from becoming useless for cultivation may be as great as the value of the lands affected. Without it the money invested in them, together with the cost of improvements, may be, practically, a total loss.

In addition to lands actually reclaimed, or given protection, drainage is an indirect benefit to adjacent areas. It is difficult and in many cases impossible to place an estimate on the value of these benefits. They may be in the form of better sanitary and health conditions, better roads and other means of transportation, larger areas under cultivation and consequently greater values of taxable property. Another benefit, and one which is probably of equal importance to all others, is the confidence which drainage gives to a community. Lands which are in part affected by seepage and alkali, are viewed with suspicion. The extent to which they may become unfit for cultivation cannot be foretold. When the seeped and threatened portions are reclaimed and protected, confidence in the entire area is restored.

Value of Lands and Crops.—The income from drainage is derived from the increased value of land and crop production. Drainage, in itself, is generally not productive of direct revenue. It supplies nothing that can be sold except in rare instances where there may be a demand for drainage water for irrigation or other purposes, and even in this case the water may belong to others than the owners of drains.

The value of land and also the crops that can be grown are both subject to wide variations and depend upon soil, climate and other local conditions. The values of lands that have been drained and put under cultivation may be said to range roughly from $100 to $500 per acre for farming purposes. Even this upper limit may be exceeded where conditions are especially favorable for growing and marketing high-priced crops. The profits due to increased values belong to land owners. The land, in turn must be security for its share of the cost of constructing the drainage works.

The profits of drainage measured in terms of increased land values and crop production are generally large where conditions

are favorable. Lands which before they were drained, would not produce sufficient to justify farming them, have in many instances been made to pay returns on $100 and upward per acre.

To properly estimate the increased value of profits resulting from drainage the speculative value of lands in a wet and unproductive state should be eliminated. The price at which such lands are frequently held may make it impractical from a financial standpoint to attempt their reclamation.

Accessibility of Lands.—Transportation facilities and accessibility to centers of population have a marked influence upon the values of land and the crops that they will produce. Transportation facilities are necessary for carrying farm products to market quickly and at a reasonable cost; also for carrying supplies and equipment to the land. Centers of population, that is towns or cities, are needed to furnish markets for the produce of the land; they also provide sources for obtaining supplies and add to the convenience of the population near to them, a condition which greatly enhances land values.

Lands which have been reclaimed by drainage, usually, are well adapted to the raising of garden products and other high-priced crops. Produce of this kind, if grown on a large scale, requires careful attention to market it without loss or waste and at a price which will yield a profit to the grower. The producer must be located near to a city or town, which furnishes a market, and to which he can deliver his products, or he must be provided with adequate means of transportation to distant points. The latter often requires special facilities, for making shipments, which can be gotten only through the coöperation of a large number of individuals.

In remote localities where markets have not been established and where transportation facilities are not available they must be provided before many of the better-paying farm products can be profitably grown. For most of the staple crops, such for example as cereals and also for live stock, markets are generally available regardless of location. Staple products can be stored or held for favorable conditions for their disposal without deterioration or loss, the profits from them, consequently are not dependent upon immediate transportation.

It is necessary to consider, in each particular case, whether lands are favorably situated for growing high-priced special products; also whether soils and climatic conditions, on reclaimed wet areas, are suitable for producing many of the staple crops.

Cost of Drainage.—One of the questions first asked concerning drainage is the cost. This must be answered for the promoter who attempts to carry through a drainage enterprise, for the land owner who obligates himself to pay for it, and finally for the capitalist who may be asked to finance its construction.

Preliminary estimates of cost are often desired in advance of thorough engineering examination and study. These when so made are frequently nothing more than an expression of opinion, based possibly upon what drainage works have cost in another locality. Where conditions are sufficiently similar, to require the same general character of works, estimates made in this manner may be of value. When conditions vary widely, an estimate made by comparison may be greatly in error.

It is difficult to make an accurate estimate of the cost of draining an area, in advance of actual construction, on account of the uncertainties regarding the extent of works that may be required. It is of course possible to plan certain works, and to estimate within a reasonable degree of accuracy the cost of their construction. It is not always possible to say that the works as planned include all that is necessary, and no more than is required to accomplish the desired results.

It is not always possible, in advance of construction, to work out final and complete plans for drainage that will prove both effective and economic. In this drainage differs from many other branches of engineering. It is possible to make a design for a structure such as a bridge or building, and include practically every detail that is required and yet contain nothing that is not needed. A water supply or irrigation system can be so laid out that it will deliver water to all of a given area without duplication or including any work not actually required. It is not possible, as stated already, to tell exactly what the effect of a drain will be, and with the most carefully worked out plan it may be found, after construction, that additional drains are necessary or that some parts of the system, as built could have been omitted or modified so as to have reduced the cost without sacrificing efficiency.

A drainage system may include the works necessary to unwater lands and make them suitable for the growing of certain crops, or, in addition thereto, it may include works intended to further improve soil conditions and bring them to the highest possible state of cultivation. It is necessary in undertaking to estimate

the cost of a system to have clearly in mind what it is intended or expected to accomplish. On account of the many uncertain factors involved in the work, and the various interpretations that may be placed upon the term drainage, its cost is subject to wide variations.

The maximum cost per acre that may be considered economically feasible varies greatly for different areas. It depends ultimately upon the increased value which drainage gives to the land. The profit that may be realized through the improvement of land is becoming more to be recognized, and the limit of cost per acre that is regarded feasible for this purpose is being gradually raised.

Naturally the first drainage work was done where conditions were most favorable for it, and the resultant costs were low. The results obtained from these relatively inexpensive developments have led to the taking up of more difficult and more costly ones. A few years ago an expenditure of $10 per acre, for drainage, was about the maximum amount to receive favorable consideration. This has increased until an expenditure of $50 per acre is not now uncommon, and even this amount may be greatly exceeded where the increase in land values is sufficient to make the investment profitable.

Other Costs.—In addition to those for constructing drainage works, there are other costs that must be considered. Reference has already been made to other items necessary to develop an agricultural area and attention called to some of the expenses incident to such development. One of the items frequently overlooked is the cost of clearing and preparing land for cultivation. This frequently has been done by the land owners and often no account kept of its cost. It must be remembered that this is as essential for making land productive, and increasing its value, as the construction of drainage or other engineering works, and the expense of doing it must be considered.

On areas that require irrigation; lands must be leveled and prepared for the proper distribution of water over them. In this case the cost of irrigation works must also be included as a part of the total expenditures for reclamation. In the humid areas, when irrigation is not practised, the requirement for leveling and preparing the surface is not so exacting; but some work of this character is generally necessary for the best results. The cost of clearing and preparing land for cultivation may amount

to 50 per cent. of the cost of drainage works and in special cases it may equal or exceed it.

In addition to a general drainage system, other works, of a minor character, may be required on individual farms. This work frequently is not included in a general estimate for drainage; but when necessary it must be done and its cost borne by the individual tract it is intended to benefit.

In addition to construction and costs of preparing lands, there are also administration, engineering and legal expenses for which provision must be made. These may amount to 10 per cent. or more of the construction charges.

Drainage Organizations.—The first attempts at drainage, so far as known, were made by individuals to relieve wet portions of their own farms; these were followed by combined efforts of small groups of persons working together on areas where more than one farm was involved. From these experiences, the advantages of combining larger tracts under one comprehensive system gradually became apparent.

Drainage work is essentially coöperative in character. An efficient and economical plan requires, generally, that drainage waters from differently owned tracts, be carried through a common outlet, or even collected by the same main drain. The land owners must coöperate in the matter of rights of way, and in construction, or payment of cost, of the necessary works. This requires some form of responsible organization to handle the executive features of the work.

Experience has shown that voluntary coöperation is not best suited, or even effective for carrying on drainage on an extensive scale. The location and character of outlets and drains, the acquiring of rights of way, and determining the amount of compensation for it, and also for damages to property are questions upon which it is difficult for men to reach an agreement. A land owner may refuse permission for a drain to cross his property and private individuals do not have the right of eminent domain and cannot condemn. There is no method by which a voluntary organization can enforce payment for benefits conferred on lands of an owner, who refuses to subscribe.

To meet the needs for an organization to effectively accomplish work, practically all of the states have enacted legislation authorizing the formation of drainage districts. These are a form of corporation which act through a board of officers, and when le-

gally constituted are authorized to transact business necessary to the reclamation or betterment of lands through drainage. They are financially responsible, and may enter into contracts, borrow money and issue bonds in the name of the district. They are authorized in accordance with the law to distribute drainage charges over lands included within the district, levee taxes for the payment of these charges; and to use the power of the state or county for the collection of these taxes. A drainage district has the power of eminent domain and may condemn lands needed for its purposes; and may hold and convey property.

The formation of a district may be initiated by filing with the court, or other proper official, a petition signed by the required number of land owners within the proposed district. The number of petitioners required varies for different states; in some, one is sufficient; while in others the majority of land owners or the owners of the majority of the lands is required. This provides a means whereby the majority, and in many cases less than a majority, of the owners, or of the lands, may initiate action against the will of others who may oppose it. It is intended to prevent a few individuals retarding or obstructing drainage improvements.

Apportionment of Drainage Costs.—As has been stated the charges for drainage works must be borne by the land. It remains to determine how these charges shall be distributed over the lands affected. It is manifestly the case that drains will have a greater influence upon some portions of an area than others; also that some lands, even though located within the boundaries of, or adjacent to a wet area, may not require drainage for their betterment or protection. This applies particularly to the higher portions of a tract and also where soil conditions are favorable for natural drainage.

The generally accepted theory is that costs shall be assessed against the land, in accordance with the benefits which it receives from the drainage works. The most practical method for doing this is to determine the benefits which will accrue to each tract, on account of drainage; the amount that each shall pay will then bear the same ratio to the benefits it receives as the total cost bears to the total benefits. If the total benefits are less than the cost the project cannot be regarded as financially feasible. It follows from the above that the owner of a naturally well drained tract should not be required to contribute to the cost of works

for draining adjacent wet lands unless he also receives a benefit therefrom.

The benefits derived from drainage, as has been stated, are many and of various forms. Some of them are special and apply directly to the particular lands that are drained, others are more general in character and may apply to an entire community. There are many factors to be considered in determining benefits; the various details of which cannot be discussed here. In making assessments for drainage improvements under state laws, it is the general rule to base them upon special benefits which the improvements are intended to confer. It is held also that the benefits must relate to a purpose for which the lands may reasonably be used.

A high area situated in the midst of, or adjacent to a swamp may be naturally well drained and yet undesirable or unsuitable as a place for man to live; it may have little or no value for agriculture or any other purpose on account of its inaccessibility to markets and transportation. Drainage, and the bringing into cultivation of the adjacent wet lands, are unquestionably a benefit to such an area, even though no change is brought about in its soil conditions. Whether an assessment can be made against the land for benefits of this character may be open to question, and require special consideration.

On irrigated lands, the apportionment of drainage costs, presents questions differing fundamentally from those of the humid areas. On the latter swamps and other wet lands have resulted from natural causes which, generally, have existed for long periods of time. The owners of such lands had an opportunity to know the condition before acquiring them. It is to be assumed that the price paid for swamps and other wet areas was less, generally, than that paid for areas that did not require drainage before they could be cultivated.

In the arid region, where irrigation is practiced on an extensive scale, seeped and wet lands are quite generally the result, directly or indirectly, of such irrigation. The bringing of an irrigation supply onto the land has resulted in filling the subsoils and caused a rise in ground water until portions of the irrigable area have become too wet for cultivation. The same agency that has made irrigation and development possible, has contributed also to making some of the land unfit for use. It was not possible, in advance of irrigation, to determine definitely what, if any, areas

would be affected by seepage, and no difference in the cost of lands or the bringing of water to them could be made on this account. In many instances, lands which gave the best returns and commanded the highest price, for the first few years after irrigation was begun, have been the first to become water-logged and unfit for use. The owners of affected areas have contributed equally with others in acquiring lands and providing means for irrigation. They are entitled to protection against having their lands rendered worthless, and others who enjoy the advantages of irrigation should share the responsibility of affording such protection. In other words, where an area is brought under irrigation, provision should be made to protect any portion of it becoming seeped and useless as a result of such irrigation, and the cost of this work should be borne by the entire area. The apportioning of drainage costs wholly on the basis of special benefits, does not take into account the responsibility of an irrigated area to protect lands within it from becoming seeped and non-productive through canal losses and excess use of water in irrigation.

Possibilities of Development.—There are large opportunities for development by drainage throughout the United States. No single factor is more important in crop production than the proper regulation and control of the moisture content in the soil. Through this the lands now under cutlivarion can be improved and made to yield greater returns. The ultimate profits that may be realized from permanent land improvements are large. In addition to this drainage offers protection against loss due to unusually wet years; in this it may be considered as an insurance to the farmer.

The agricultural areas of the country may be increased through drainage and reclamation of wet, and in their present condition, useless lands. It is not to be inferred from this, that all swamp areas are susceptible of being brought under successful and profitable cultivation. There are large areas, however, that can be reclaimed and offer opportunities for safe financial investments.

In addition to the profits that may be realized, by individuals, in the form of increased land values and crop productions, the development of useless lands is a distinct gain to the state and nation through the wealth it creates. Increasing agricultural areas contributes directly to the fundamental sources of wealth

of the country. It furnishes homes and additional sources of food supply for the growing population.

The clearing away of swamp lands creates better sanitary and health conditions. It makes possible also the building and maintaining of better roads and other transportation facilities. These are public benefits the extent of which cannot be measured. The possibilities offered for further drainage development are worthy of consideration by the engineer, land owner, capitalist, and statesman.

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